BRITISH WELDING JOURNAL

1960 JULY

VOL. 7 NO. 7

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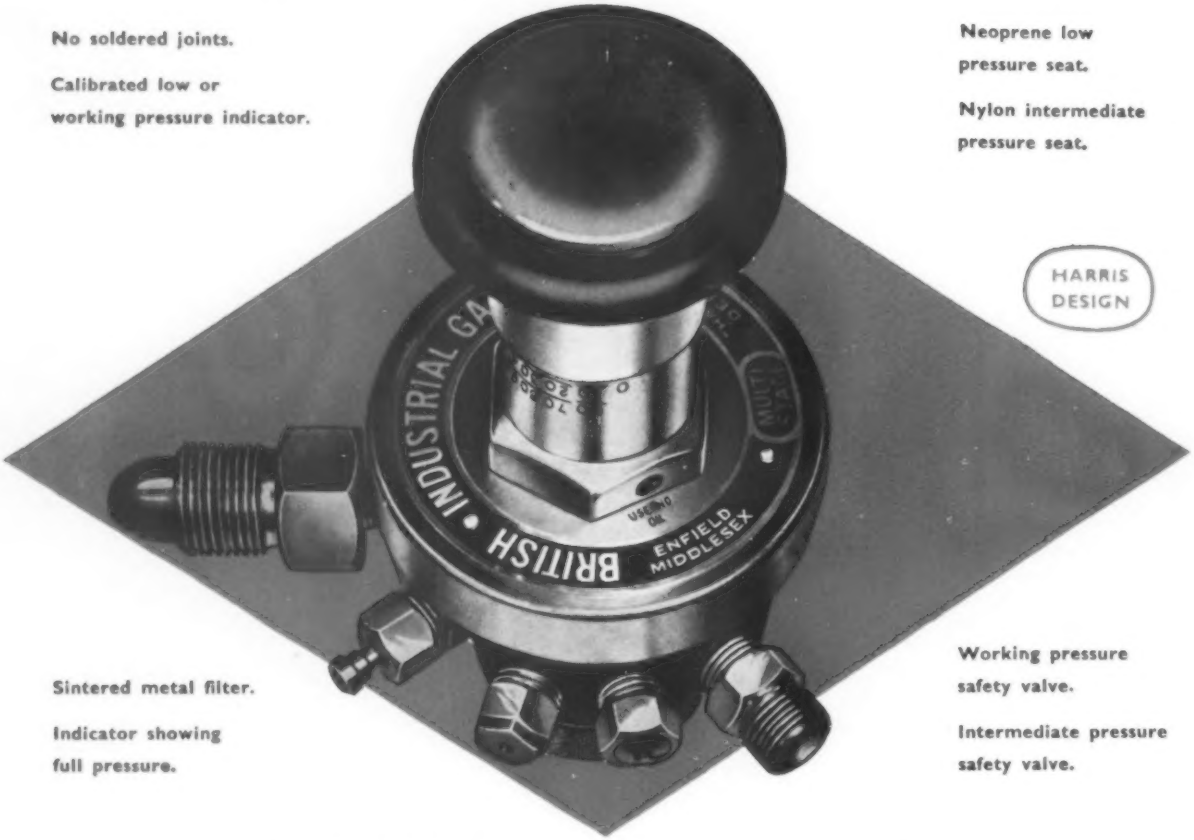

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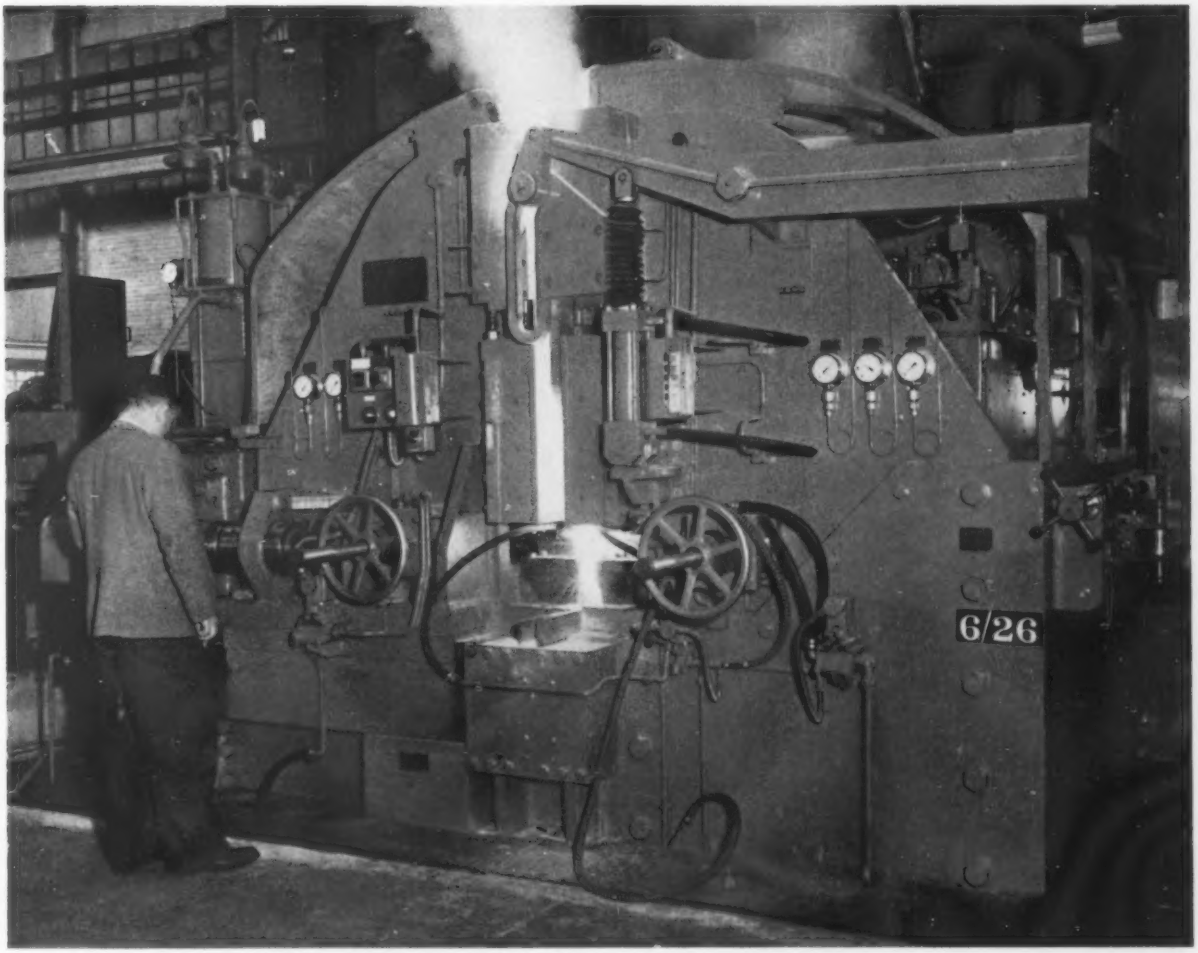

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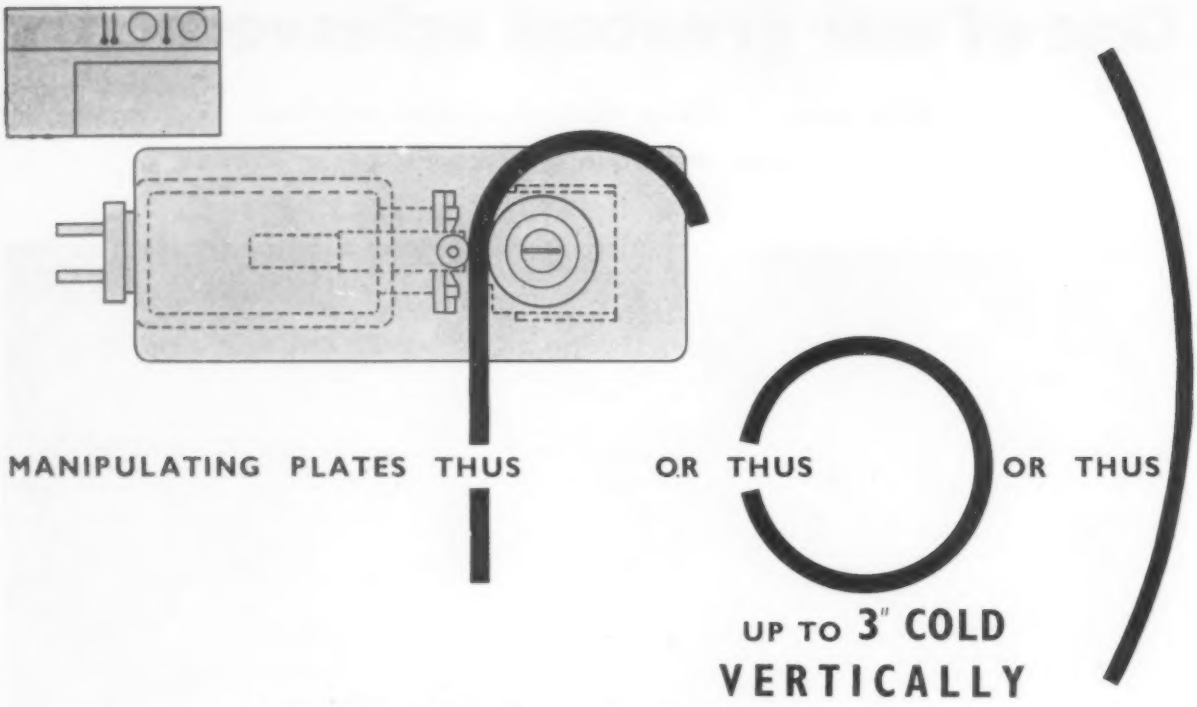

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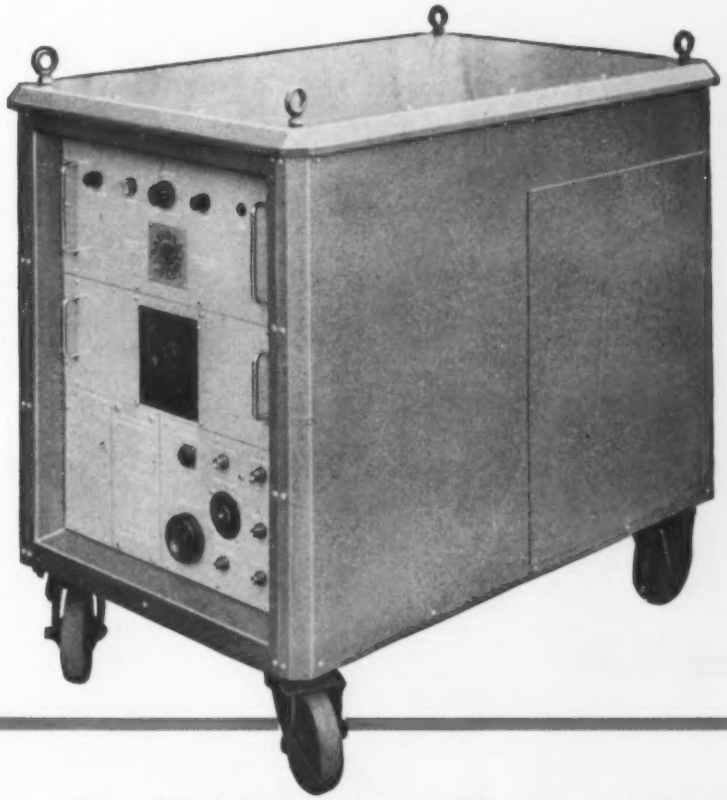

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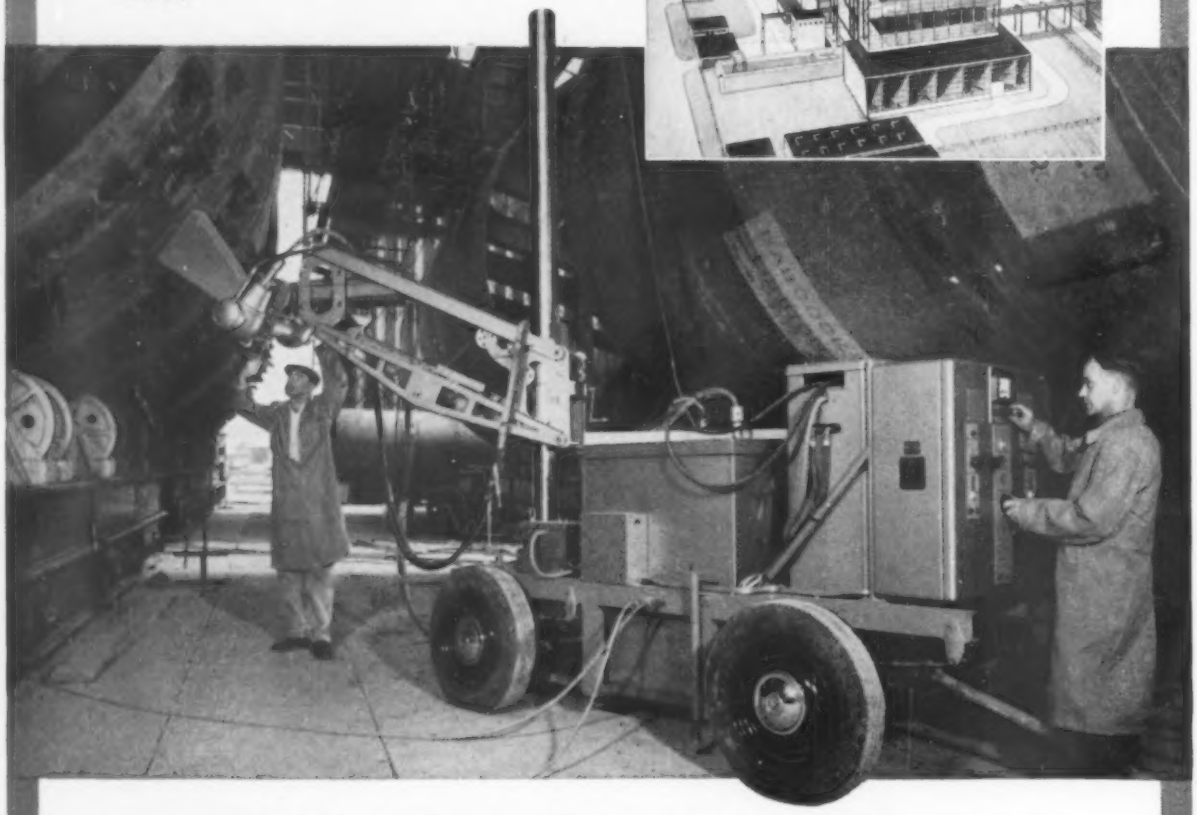

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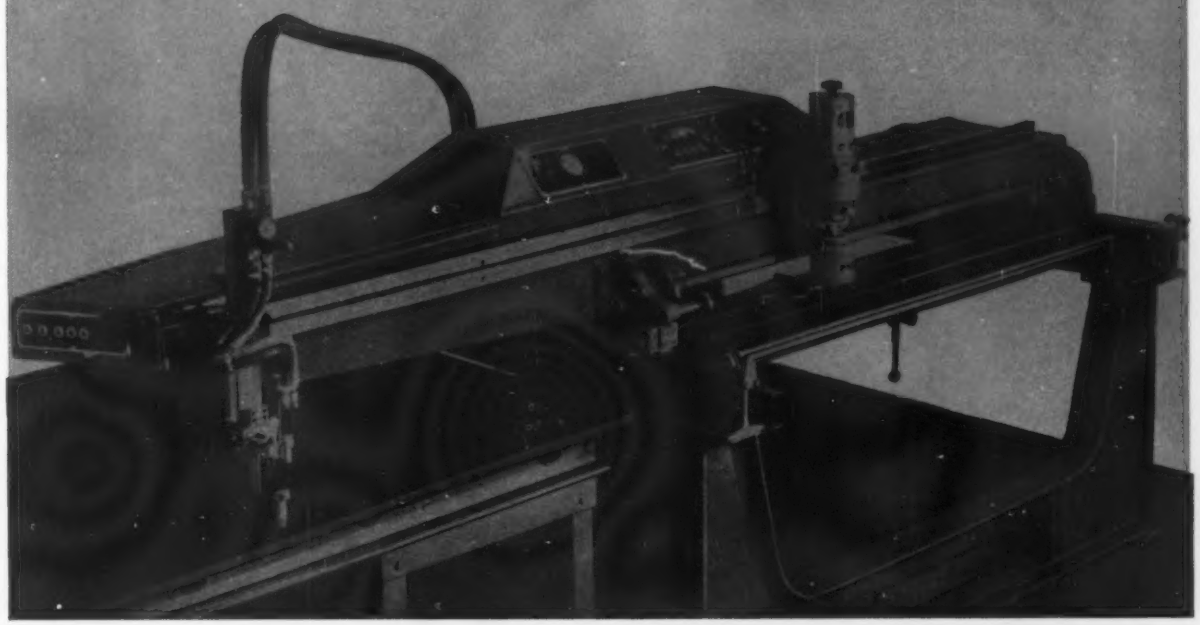

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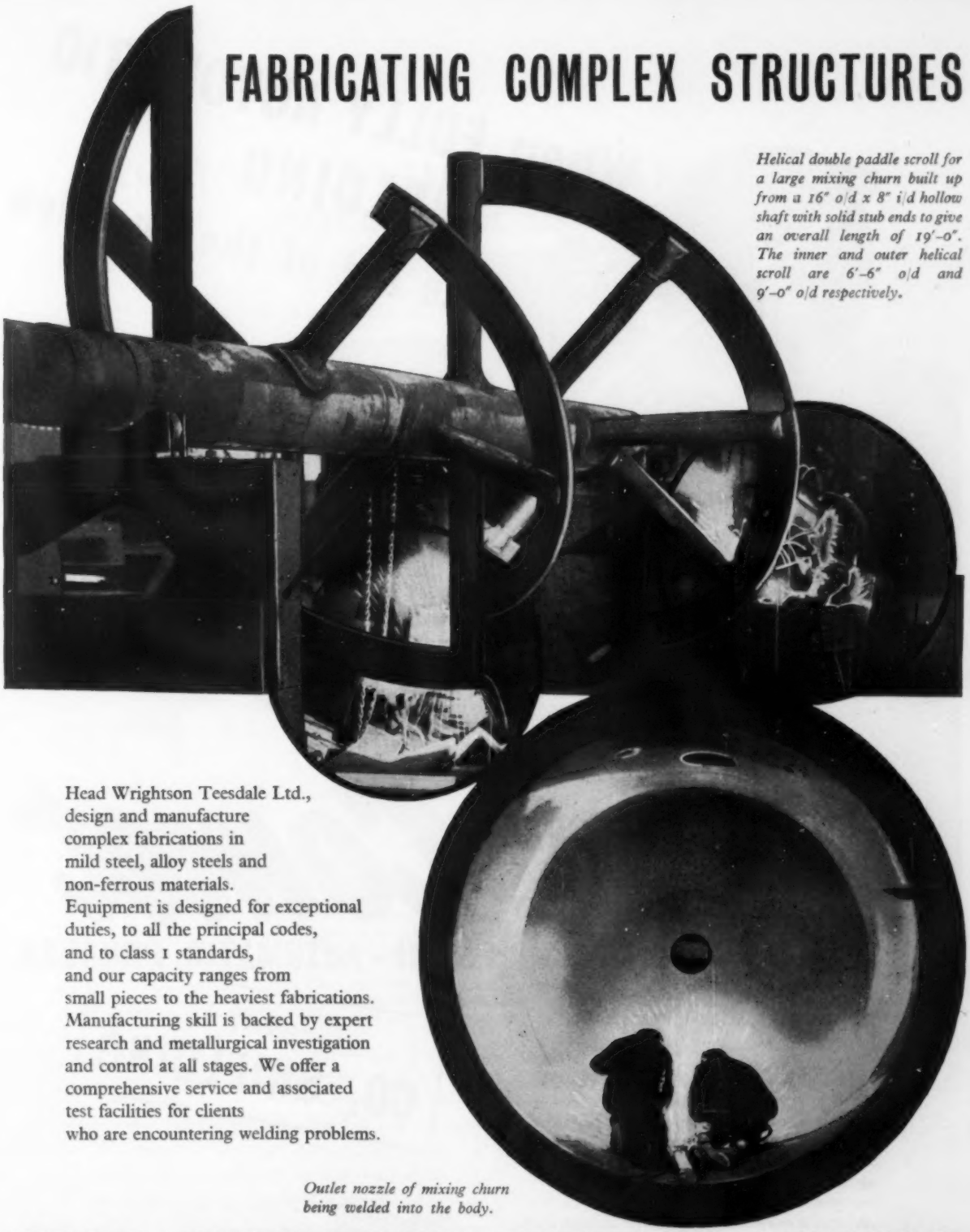

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Outlet nozzle of mixing churn being welded into the body.

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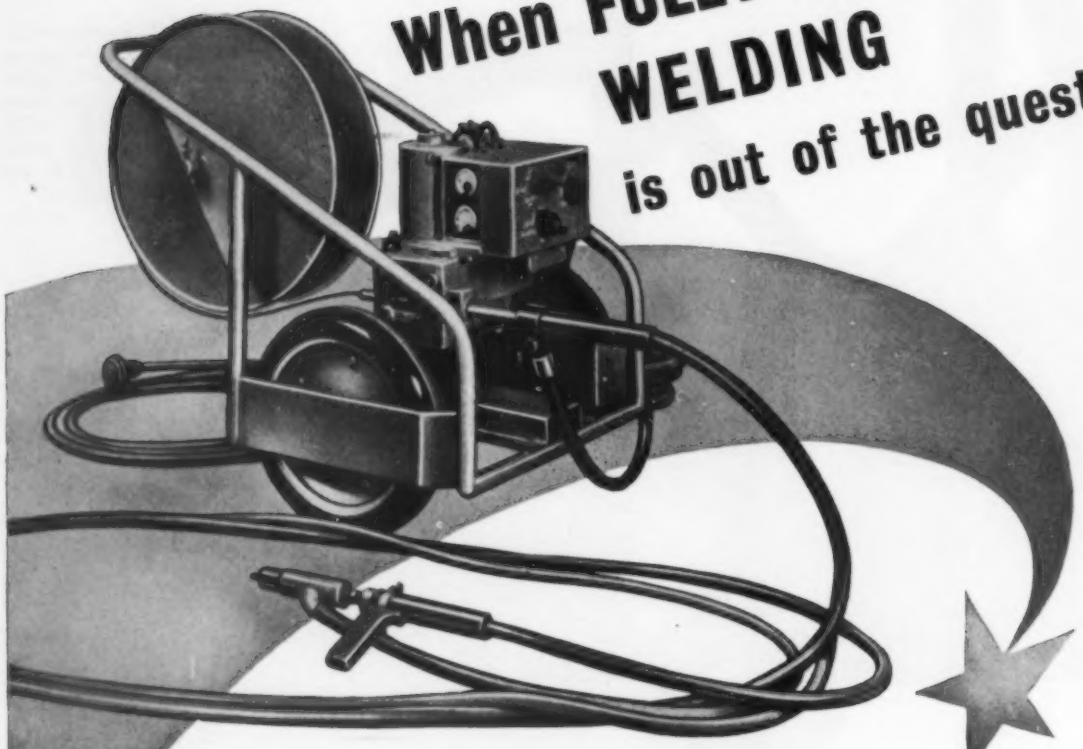

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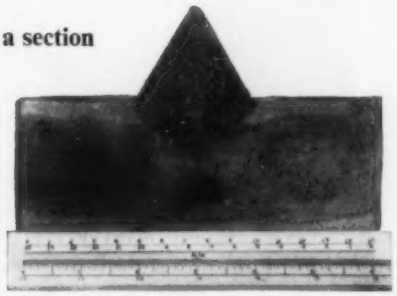
ELECTRO-SLAG WELDING—NEW APPLICATIONS

THINKING AT THE DESIGN STAGE

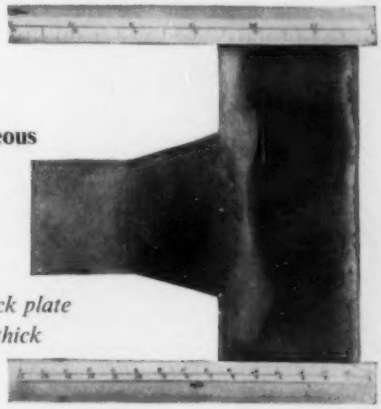
A new process frequently offers unique opportunities for improvement in quality, for lowering of production costs or even scope for truly original application. Re-assessment of problems in design may be possible. To promote new thinking at the design stage two new applications for electro-slag welding by the Rockweld-Vus Vertomatic machine are described.

Adding a section



(*Above*) *One of many shapes of section which can be added to a plate or existing section*

A homogeneous T-weld



(*At right*)
Two-inch thick plate Teed to 2⅜" thick plate

This particular section was obtained with a single water cooled shoe on a flat surface. It could equally well be applied to a cylindrical surface. The shape is only typical of many which could be adopted and quite a wide range of low alloy steels can be imposed on dissimilar steel plates or forgings. The considerable depth of penetration in this example will be noted but penetration can be varied to suit particular requirements.

ADVANTAGES OF THE ELECTRO-SLAG PROCESS

Vertical Welds in heavy material, impossible by conventional methods.
Unlimited thickness can be welded.
Manipulation of work into position suitable for conventional welding, difficult and expensive with unwieldy heavy sections, is avoided.
Elaborate plate preparation is eliminated.
All welding is done in a single pass—the deslagging and chipping unavoidable with multi-pass welding is eliminated.
Comparative little flux powder is needed and there is no need for continuous flux recovery.
High thermal efficiency allows outstanding economy in welding power consumption.
Can replace heavy forging and casting of heavy parts.
Plate need not be accurately aligned.
The process is fully automatic.
Very high rate of deposition—up to 40 to 50 lb. per hour.
★ ***Production time can be rated in hours instead of days, with less welding labour.***

T-welds in heavy plates or forgings often present problems in design and construction. Homogeneity and shaping of such welds may be difficult in execution by conventional welding methods. Electro-slag welding overcomes such difficulties, provides 100% radiographic results and mechanical properties superior to plate material for most constructional steels. No plate preparation is necessary for this weld.

WELDING DATA

Welding data provided on this experimental section is not necessarily the optimum which could be derived from further tests:

Welding current	600/650 amps.
Welding voltage	36/38 V
Vertical speed of welding...	48" per hour
Wire consumed	0.5 lb. per inch of weld
Plate thickness	2¼"

WELDING DATA

This weld was carried out with a single wire of ⅛" diameter. A fixed water cooled shoe was placed on one side of the preparation and a special movable shoe on the other side, using a standard Vertomatic machine.

Welding current	525/550 amps.
Welding voltage	45/46 V
Vertical speed of welding...	31.5" per hour

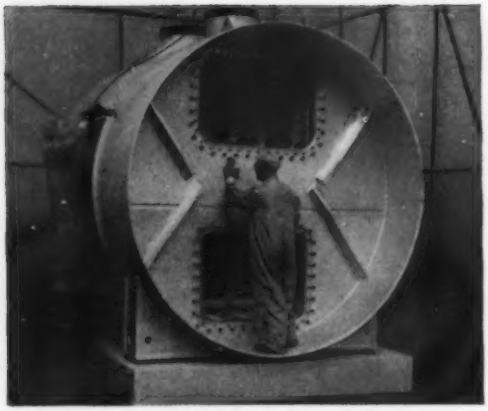
The name of Fairey...

To most of us the name of Fairey has always been linked with famous aircraft, not the least of which was the Delta 2 in which the World Absolute Speed Record was raised to 1132 m.p.h. But in recent years the interests of the Company have been spread widely throughout the field of industry.

For example, just outside Stockport, at Heaton Chapel, Fairey Engineering Ltd. operates a large plant for the fabrication and welding of aluminium and steel structures. The engineers here have developed special techniques based on the extremely high standards of quality inspection demanded in aircraft production, and for many years the plant has been engaged in making equipment for the United Kingdom Atomic Energy Authority, where standards are equally high. The company is expanding its training school for welders and building a new block of Metallurgy and Welding Engineering Development Laboratories.

Fairey metallurgists and quality inspection engineers attach special importance to X-ray and gamma-ray inspection of castings and welds, and the radiographs are carefully filed to provide proof of sound casting and welding techniques. The greater percentage of products leaving the Heaton Chapel works are radiographed.

And for this vital evidence of sound workmanship Fairey Engineering relies on Kodak "Industrex" X-ray Films—the last vital check in a chain of quality control techniques.



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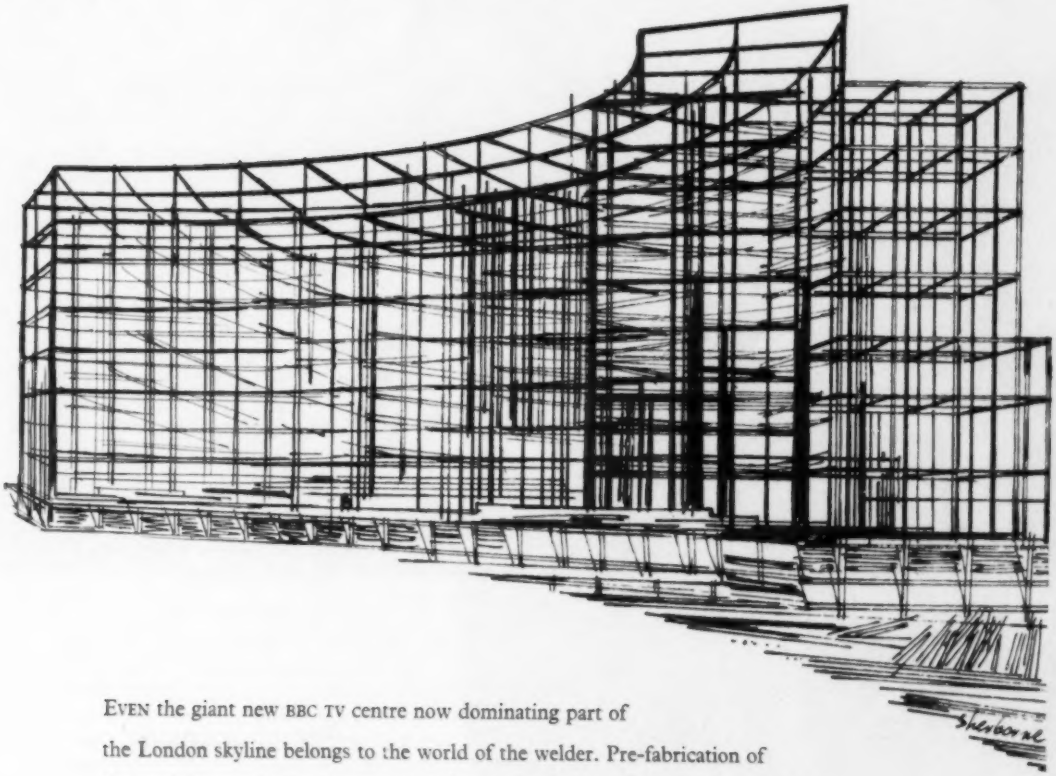

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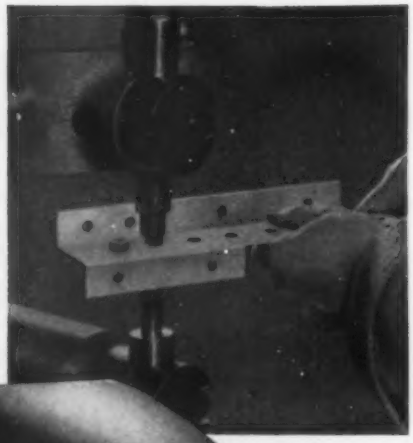

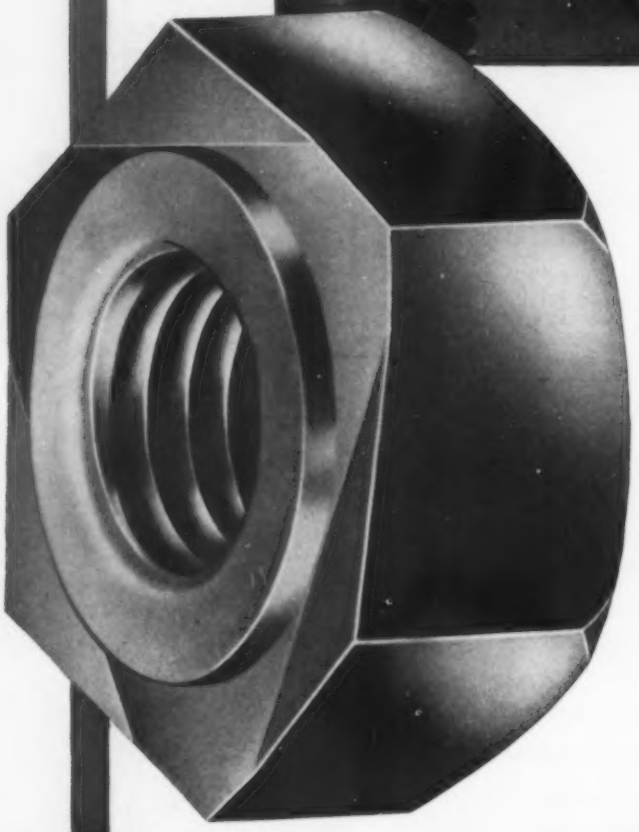

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BK 24	1200	140	—
BK 24A	1200	140	Integral
BK 24B	1200	140	Clamp on
BK 34	2400	355	—
BK 34A	2400	355	Integral
BK 34B	2400	355	Clamp on
BK 42	600	56	—
BK 42A	600	56	Integral
BK 42B	600	56	Clamp on
BK 66	300	22·4	—

* Ratings are for welder control service, with two valves in inverse parallel at any voltage from 250-600v. r.m.s.

Rectifier types

Type	Maximum peak voltage (Kilo volts)	Maximum average current at peak voltage (Amps.)
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BK 46	2·1	150
BK 56 †	20·1	150

† Tentative ratings.

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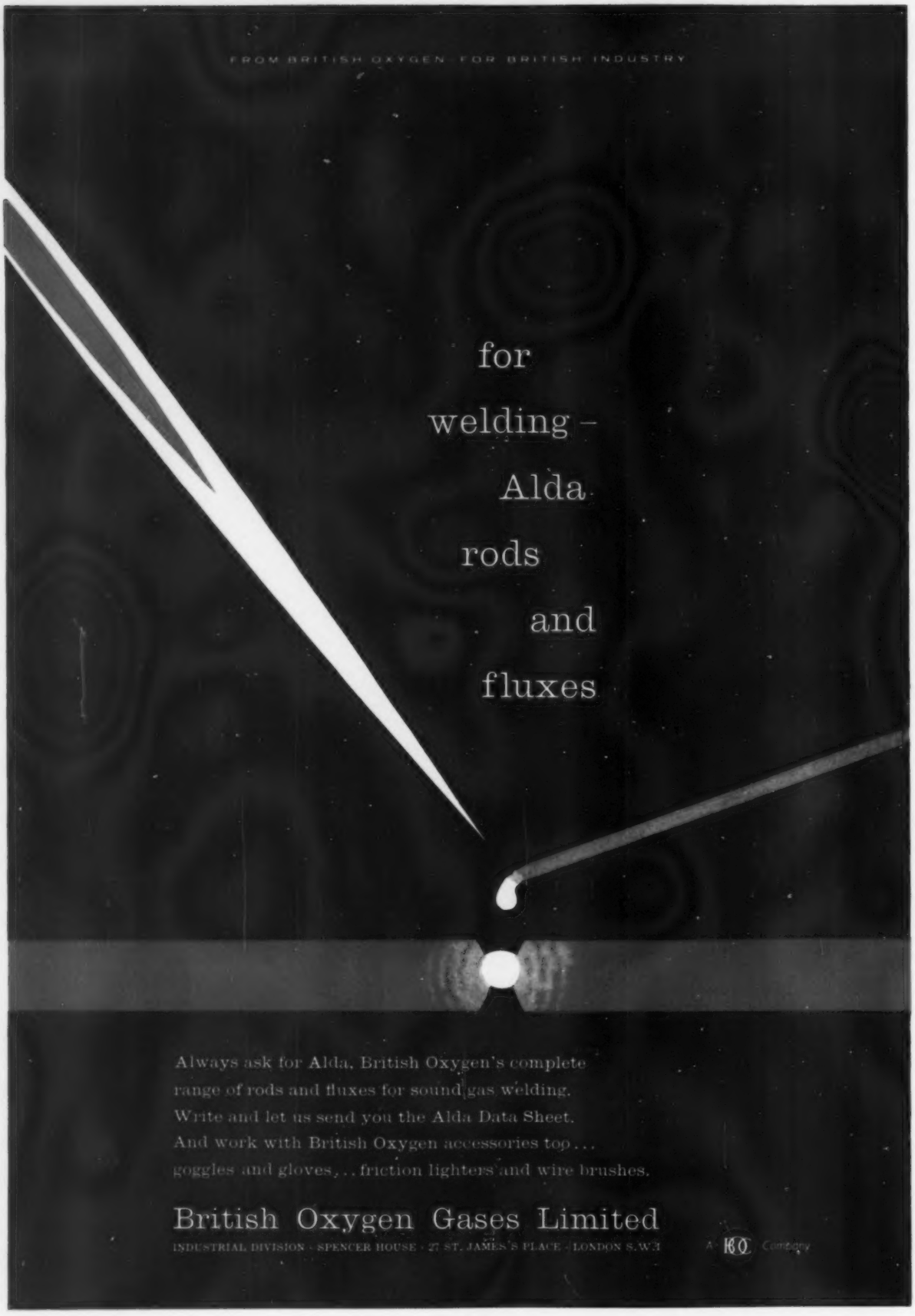

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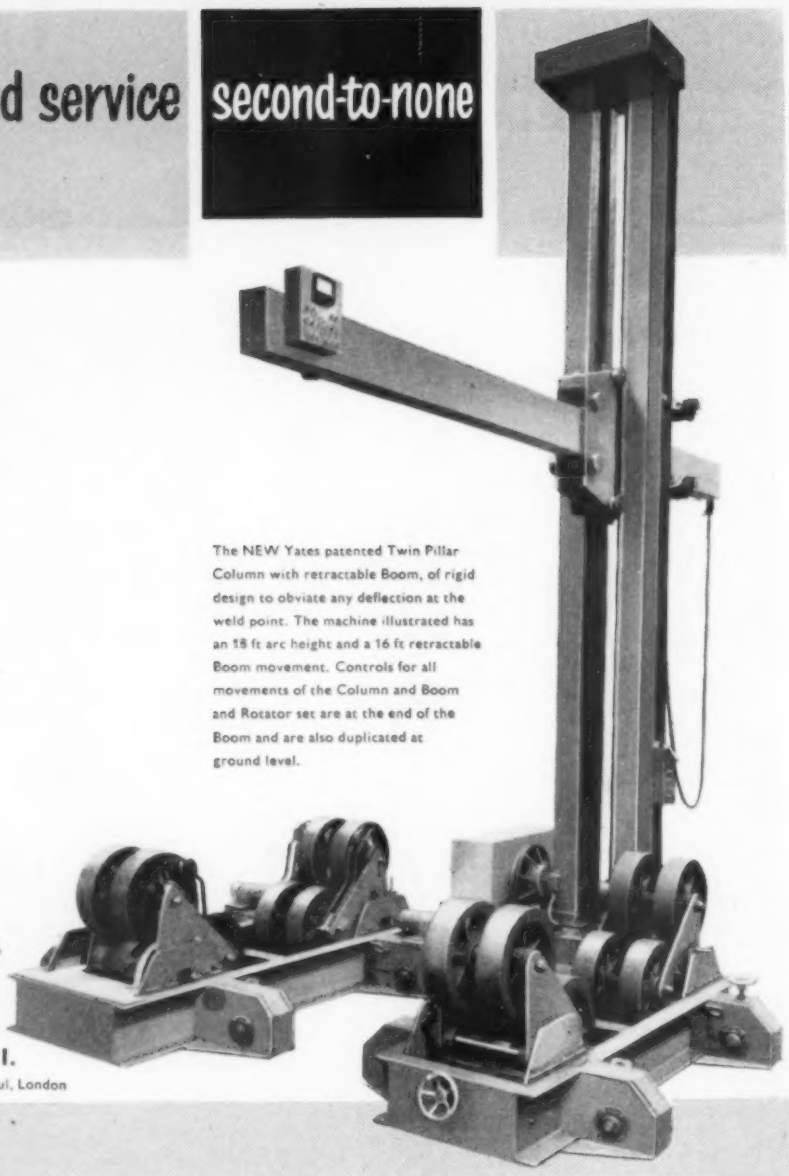

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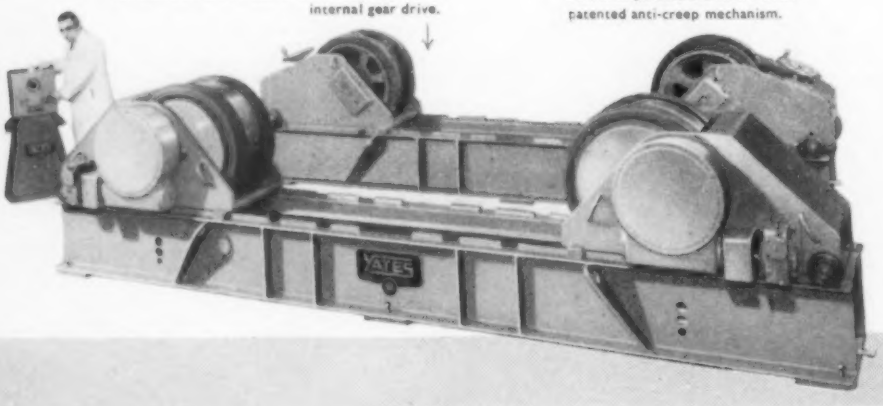

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BRITISH WELDING JOURNAL

OFFICIAL JOURNAL OF THE INSTITUTE OF WELDING AND THE BRITISH WELDING RESEARCH ASSOCIATION

Incorporating the *TRANSACTIONS* of the Institute and *WELDING RESEARCH*

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JULY 1960
Volume 7 Number 7

Subscriptions
Members free:
Extra copies at 7*s.* 6*d.* each
Non-Members:
£5 per annum
Single copies 10*s.* each

Published Monthly

Editor-in-Chief: G. PARSLOE, M.A.
54 Princes Gate, London, S.W.7
(Knightsbridge 8556)

Executive Editor:
C. ROWLAND HARMAN, B.Sc. (Eng.)
Editech
77a Chertsey Road
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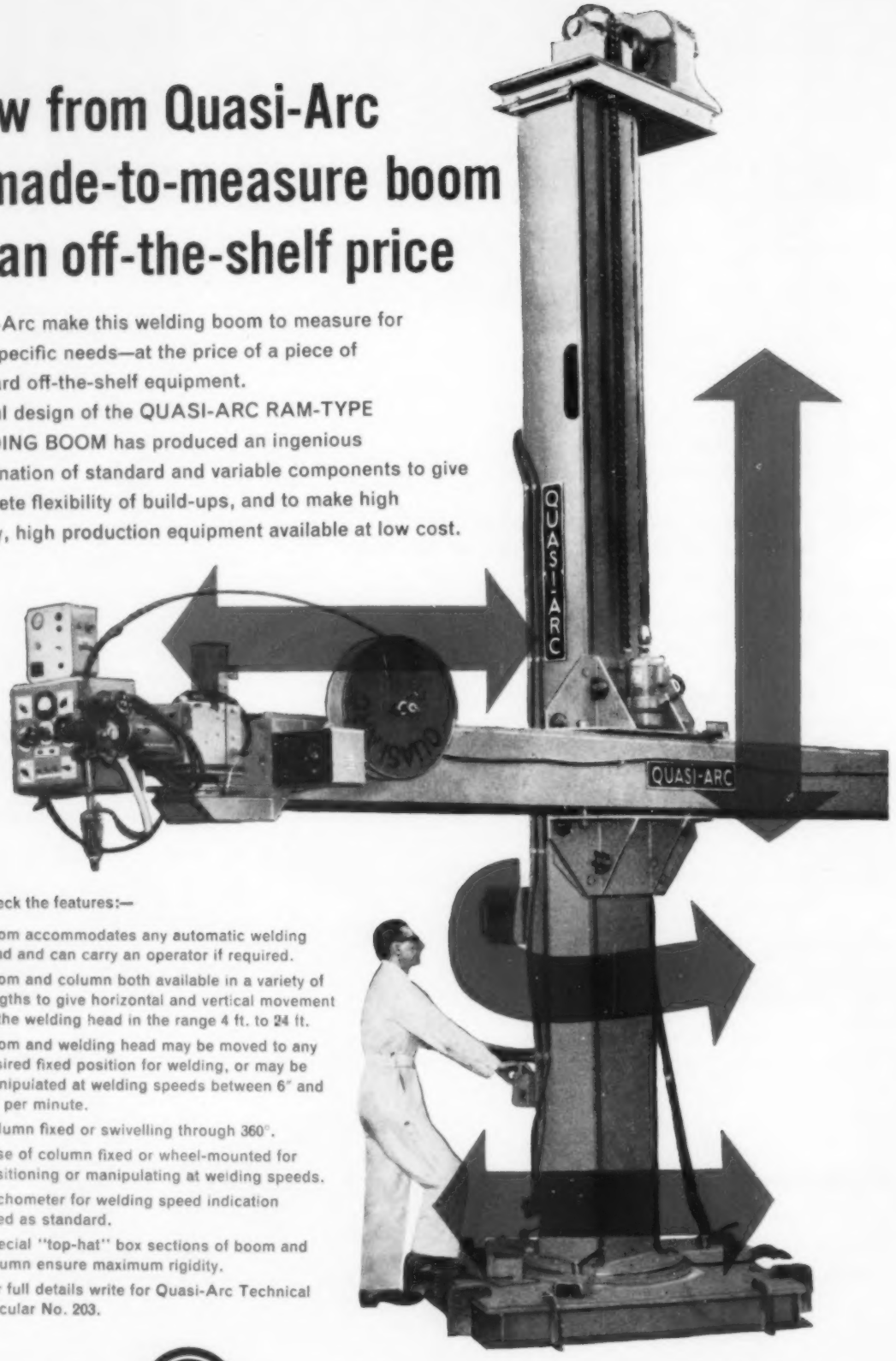

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Welding
TECHNOLOGY

Fusion Welding of Beryllium

By T. J. McDonald, N. F. Eaton and D. B. Wright

Apparatus is described for experimental tungsten-arc inert-gas autogenous fusion welding of beryllium.

Satisfactory welding conditions were obtained for a variety of weld designs of beryllium fabricated from ingot and sintered powder material. Work was concentrated on fuel element end cap designs where weld preheat and subsequent cooling rate were found to be critical factors in eliminating cracking when using flowing argon as an inert-gas shield. Welding in a static, pure argon atmosphere was found to require less critical control of these factors.

THE utilization of nuclear energy as a source of power has necessitated a re-appraisal of the properties of many materials in terms of the rather special requirements of nuclear science, and as a consequence some metallic elements previously of only limited interest have assumed new economic significance. One such metal is beryllium, which has a low capture cross section for thermal neutrons and also adequate strength and corrosion resistance at temperatures of the order of 600°C. It is therefore of potential value as a fuel-canning material for use in gas cooled reactors. However, the technology of beryllium poses some rather special problems; in particular, working and fabrication involves a rather serious health hazard, whilst by comparison with most other constructional materials the wrought metal is brittle.

Weldability is a particularly important property of materials used in the nuclear energy industry, and as part of a general programme of research carried out by A.W.R.E. concerned with various aspects of the metallurgy of beryllium, a preliminary study has been made of its fusion welding characteristics.

Health Precautions

The toxicity of beryllium, particularly in finely divided forms such as powder and vapour, is now widely appreciated and procedures have been established for its safe handling.[1,2]

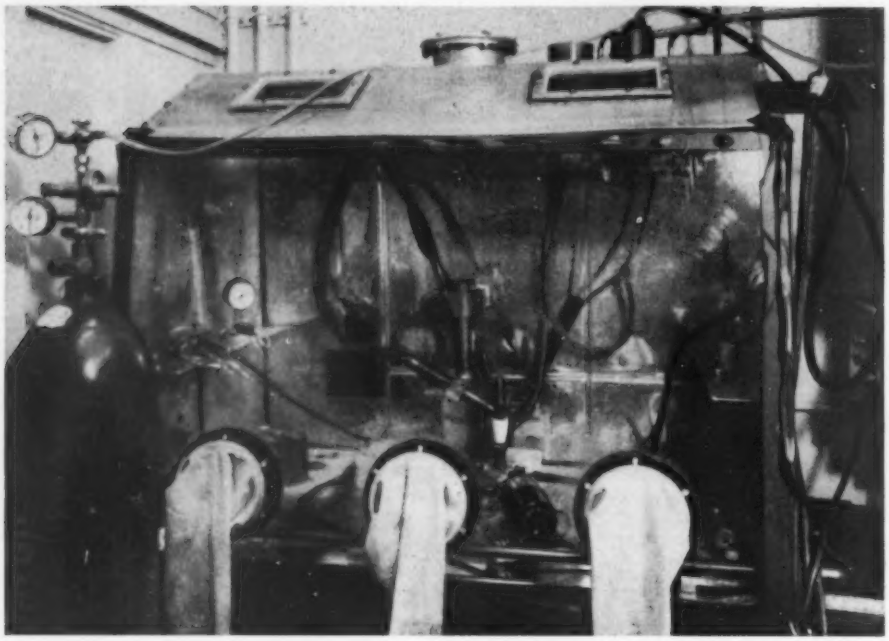
All beryllium welding at Aldermaston has been carried out in laboratories equipped with air extraction and filter systems designed to ensure that atmospheric beryllium contamination does not exceed defined low concentrations. In addition, personnel are required to wear coats and shoes which are worn only in the working area of the laboratories, special cleaning and washing facilities being provided on leaving the laboratory. Any process likely to be hazardous from a health viewpoint is suitably enclosed and provided with an air extraction system. The welding operations involved in the present investigation were carried out inside a sealed glove-box (Fig. 1) that was connected to the air extraction system and maintained at a negative pressure of between 1 and 2 in. water gauge. Later experiments were conducted in a completely enclosed chamber comprising a retractable glass bell jar and sealing ring, a device which permitted evacuation before welding.

Analysis of air samples taken during welding

Manuscript received 3rd September, 1959.

Dr. Eaton is with Metropolitan Vickers Ltd. and Mr. McDonald is with I.C.I., Metals Division; both were seconded to the Beryllium Section at the Atomic Weapons Research Establishment, during the course of this investigation.

Mr. Wright is at the Atomic Weapons Research Establishment, Aldermaston.



1—*Welding glove-box (disconnected from ventilation system for photography)*

operations established that the health precautions described were fully adequate.

Previous Work

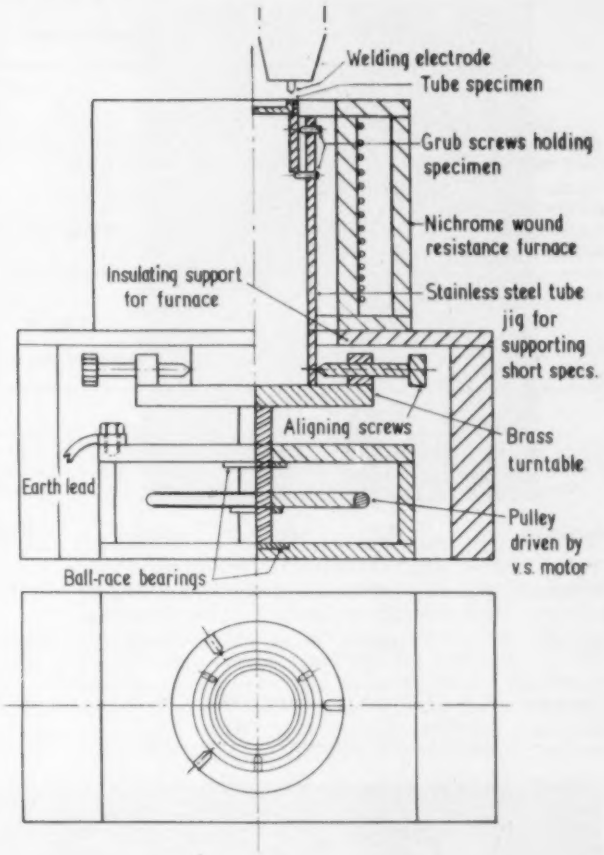
Earlier work in Britain was limited by the low quality of beryllium then available, for impurities such as chlorides and oxides prevented adequate fusion. American workers[3,4] report that longitudinal weld cracking, which apparently occurs at or near the solidus temperature, is difficult to avoid, whilst oxidation is also troublesome. Direct current, tungsten-arc welds, with the electrode negative, in plate in thicknesses up to 0·5 in. invariably cracked with either argon or helium shielding, whilst no apparent benefit was derived from pre-heating or from using reverse polarity. Weld hot cracking occurred in all purities of material available, with or without reinforcement. Oxidation during welding, which prevented good interfusion, could be controlled to some extent by the use of fluxes. Gaseous fluxes were more suitable than solid ones, which, because of their relatively high density, tended to become entrapped in the welds. Although successful joints in beryllium have been reported[5,6] no details were given other than that d.c. was employed, with helium or argon shielding and with electrodes of both negative and positive polarity. The serious difficulties encountered have lead to the development of braze-welding techniques, aluminium and Al–12%Si filler rods being employed in conjunction with the inert-gas shielded-arc processes.[4] A more elaborate approach employing electron beam welding techniques in high vacuum (10^{-5}mm/Hg) has recently been reported to give satisfactory results.[7]

Materials

Beryllium is extracted normally by two processes: 'flake' is obtained by electrolysis of fused chlorides, whilst 'pebble' is the term used to describe the product resulting from magnesium reduction of the fluoride. These primary forms are vacuum melted, when harmful impurities are removed. The ingot may then be processed directly to required shapes by rolling or extrusion or, alternatively, powder metallurgical methods may be employed. Consolidation of beryllium powder may be achieved either by vacuum hot pressing or by vacuum 'pressureless' sintering, a technique which has given excellent results.[8] The product obtained by powder metallurgical techniques has the virtue of small grain size, a feature which confers increased ductility in the wrought product.

Wrought material produced from both pebble and flake beryllium was used in this investigation but no attempt was made to determine differences in the properties of the two basic types.

Most tests were made on flake ingot, hot extruded to tube of 1 in. internal diameter with wall thickness 0·1 in., and on rod of 1·25 in. dia. A smaller quantity of pressureless sintered material was available in the form of rod 1·3 and 1·5 in. dia. respectively, whilst for preliminary work some sheet obtained by hot rolling of flake ingot, pebble ingot, and pressureless sintered material was obtained in thicknesses between 0·03 and 0·07 in. Typical compositions of materials used are given in Table I, and some properties of beryllium considered to be relevant to welding behaviour are listed in Table II, together with those of some conventional non-ferrous metals.



2—*Apparatus for welding end caps with controlled cooling rate*

Equipment

The argonarc torch, inside the glove-box, was mounted on a rack and pinion for mechanized operation. Tube-end cap welds were made on a brass turntable driven, through pulleys and rubber belts, by a variable speed electric motor. For controlled cooling tests, a 1·5 kW resistance furnace was supported above the turntable, and beryllium specimens were held in a suitable position for pre-heating and welding by a stainless steel tube jig fixed to the turntable and protruding through the furnace (Fig. 2). Sheet butt welds and fusion runs were made on a mild steel jig traversing a grooved track and driven by a variable speed electric motor. Apart from positioning, the main functions of the jig were to ensure good electrical contact between beryllium specimens and the earth lead, and to minimize sheet distortion during welding. Sheet edge welds were made by clamping specimens together and standing them on the butt welding jig. Electrical, water, and gas leads were introduced to the glove-box through appropriate seals. All other equipment was kept outside the glove-box.

In early work, specimens for welding were transferred through a tunnel at the side of the box, fitted with two air-tight doors, one opening into the box and one out, but only one being opened at any time during transfer. In later stages of the investigation, limitations of space in the laboratory required the tunnel to be detached, the opening sealed and specimens carried in and out of the box through one of the glove ports. Tests established that this procedure was safe provided that an inward draught was maintained.

Power for a.c. welding was obtained from a transformer coupled to a high-frequency spark set for arc initiation; a d.c. suppressor unit; a two-pole contactor switch; and a two-way foot switch controlling power and high frequency to the torch. Power for direct current was obtained from a 350-amp welding generator, arc starting being assisted by a polytrode high-frequency unit. Arc power and high-frequency current were controlled by separate foot switches. Both welding grade and high purity (99·995%) argon were used for arc shielding.

Preliminary Work

Chemically, beryllium resembles aluminium and magnesium in that it forms a refractory surface oxide film that is insoluble in the metal; thus, in inert-gas arc welding, dispersion of the oxide is necessary to permit adequate coalescence of the melted edges of the joint. For this reason the reports of d.c. electrode negative welding of beryllium were viewed with some scepticism, for when current of this polarity is

Table I

Typical composition ranges of material used

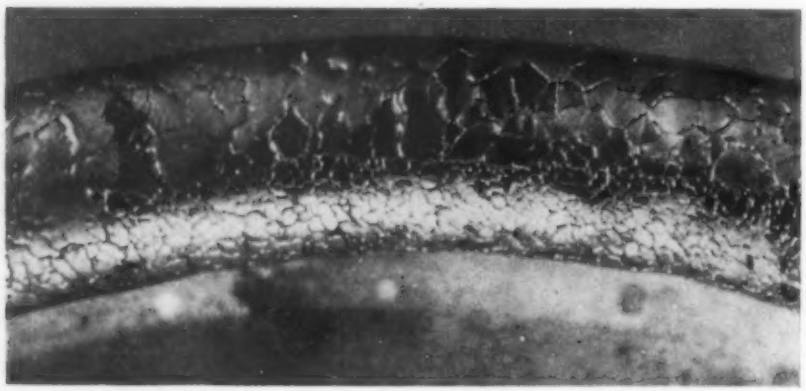
	Composition, %wt.											
Material	*Fe*	*Al*	*Si*	*Mg*	*Mn*	*B*	*N*	*Cl*	*F*	*BeO*	*Ca*	*Na*
Vacuum-melted flake ingot	0·02–0·05	0·05–0·07	0·05 – 0·15	0·008–0·010	0·001–0·003	0·0001	0·003	0·001–0·004	0·001–0·004	0·15–0·20	<0·01	<0·01
Vacuum-melted pebble ingot	0·04–0·18	0·07–1·1	0·01–0·13	0·008–0·05	0·01–0·18	—	0·007–0·031	n.d.–0·005	n.d.–0·015	0·15–1·2	0·01–0·65	0·004–0·01
Pressureless sintered powder	0·02–0·05	0·05–0·09	0·04–0·10	0·005	0·003	0·0005	0·005–0·010	0·002–0·005	0·004	0·3–0·6	—	—

n.d. – not detectable.

Table II

Properties of beryllium compared with some other non-ferrous metals

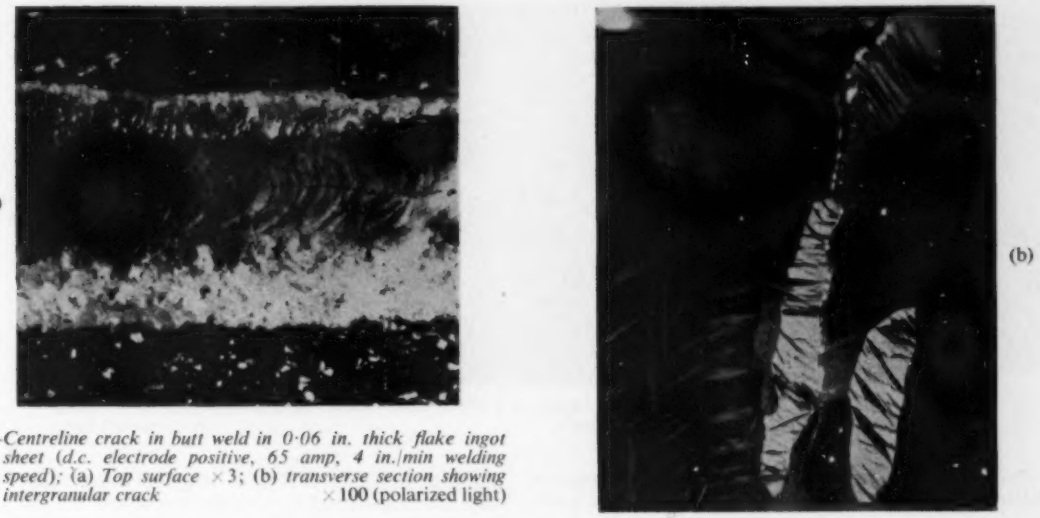
Metal	*Melting Point, °C.*	*Latent Heat of Fusion, cal/g*	*Specific Heat (0–100°C.) cal/g/°C.*	*Thermal Conductivity (at 20°C.) c.g.s. units*	*Coeff. of Linear Expansion (0–100°C.) in./in./°C. × 10⁶*	*Density, g/cu.cm*	*Metal-Oxygen Reaction at Welding Temperatures*
Beryllium	1283	Approx.300	0·450	0·40	11·5	1·85	Stable oxide formed, relatively insoluble in molten metal
Aluminium	660	94·6	0·219	0·57	23·5	2·70	Stable oxide formed, relatively insoluble in molten metal
Copper	1083	91·1	0·092	0·94	17·0	8·96	Oxygen extensively soluble in molten metal
Titanium	1668	Approx.100	0·126	0·04	8·8	4·51	Oxygen extensively soluble in molten metal



3—*End cap weld in extruded flake ingot, showing pronounced grain boundary marking. (a.c., 30 amp, 1 in./min welding speed)* ×15

employed the oxide film on the surface of the plates is not dispersed. In commercial practice, both aluminium and magnesium alloys are normally welded with a.c., to permit a more favourable heat balance for the tungsten electrode and thus the use of higher current for a given size of electrode.

Initially, fusion runs were made on $\frac{1}{16}$ in. thick sheet using d.c. with the electrode negative, the specimens having been prepared by surface grinding and degreasing. Under these conditions oxidation of the weld metal was evident and arc instability developed. No improvement resulted from altering the surface treatment applied before welding, for example by etching, nor were attempts to improve quality of the atmosphere inside the glove-box successful. Indeed it was evident even at this early stage that the glove-box employed contained appreciable quantities of air, so that the atmosphere from the viewpoint of shielding was poor. For this reason, although the glove-box technique was continued so as to avoid health hazards, no effort was made to maintain high purity of argon in the box. On the other hand, increased attention was paid to the problem of shielding the joint with argon from the torch and also to the provision of argon coverage at the under side of the weld. With improved shielding (provided by larger ceramic shields and underbead coverage from a separate supply) and using d.c. with electrode negative, welds were made



4—*Centreline crack in butt weld in 0·06 in. thick flake ingot sheet (d.c. electrode positive, 65 amp, 4 in./min welding speed); (a) Top surface* ×3; (b) *transverse section showing intergranular crack* ×100 (polarized light)

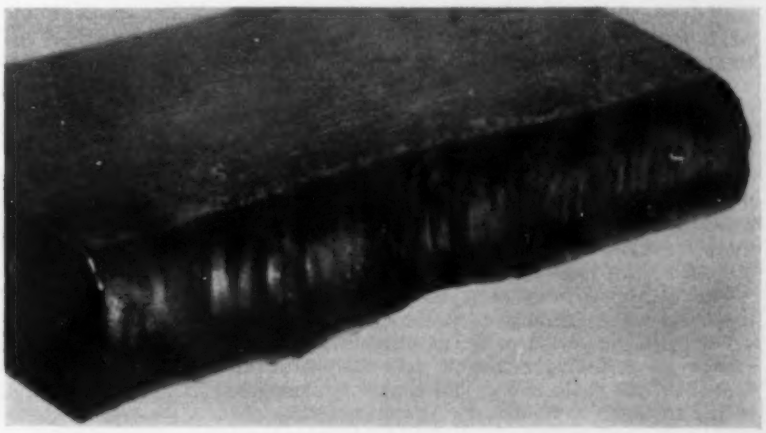
over a range of welding conditions. In every instance longitudinal cracking occurred in the fused zone and the welds were dirty, indicating that no oxide removal had occurred during the welding cycle.

When using d.c. with electrode positive, a bright clean weld bead could be produced without difficulty, indicating that oxide dispersal was proceeding as expected. Cracking however was equally troublesome, while the large molten globule of tungsten at the electrode tip, which is associated with welding on reverse polarity, was responsible for a good deal of arc instability, the arc wandering away from the point of welding and causing a surface marking on the beryllium sheet, a feature best described as 'thermal etching' and being characterized by apparent cracking at the surface boundaries (Fig. 3). This effect is thought to be due to local vaporization of beryllium under the influence of the arc.

A typical weld crack is illustrated in Fig. 4. Microscopic examination of weld sections established that longitudinal cracks were predominantly intergranular, and that transverse cracks were also present.

Tests were next made using a.c., and a considerable improvement in welding conditions was noted due to the fact that a more stable arc could be maintained over wider ranges of current for a given electrode size. However, preliminary fusion runs on sheet indicated no significant difference in cleanliness or cracking tendency from the d.c. electrode positive tests. Having established a correct condition for using a.c., several tests were made at varying welding speeds on machined and degreased flake ingot sheet in thicknesses ranging from 0·03 to 0·07 in. The results of these tests indicated that centreline cracking was reduced by increasing welding speed, and that welding speed necessary to eliminate centreline cracking was a function of parent metal grain size. For example, sheet 0·060 in. thick with grain size of 900 microns was free from centreline cracking when welded at 6 in./min, whereas material 0·030 in. thick and 100 microns grain size was free from longitudinal cracking when welded at 3 in./min. It was noted however that transverse weld cracks were present in all specimens.

Surface depressions at grain boundaries (thermal etching) occurred on all the welds made with a.c., being similar in appearance to those in the welds made with d.c.; but it was apparent that this feature was absent on the underside of the weld and this supports



5—*Edge weld in 0·07 in. thick pebble ingot sheets (a.c., 70 amp, 6 in./min welding speed)*

6—*Transverse section of part of edge weld (at right) in 0·07 in. thick sheets rolled from pressureless sintered material (a.c., 70 amp, 6 in./min welding speed)* × 36 (polarized light)

the view that thermal etching is due to arc wander, which causes local melting and vaporization of beryllium at the grain boundaries. Attemps were made to check the quality of joints radiographically but the extremely low dispersion of beryllium made this inspection of doubtful value. No features other than the large centreline cracks were revealed.

Although compositional features influence centreline hot cracking, a most important factor is the strain condition set up by the thermal cycle. It was considered worthwhile therefore to examine joints of different geometries where the strain effects due to the thermal cycle could be minimized. Edge welds were made, using a.c., on machined and degreased sheet specimens of both rolled pebble ingot and rolled pressureless, sintered material. All specimens were from sheets 0·07 in. thick and all had grain size in the range 25 to 50 microns. The cracking tendency was not as pronounced as in butt welding, and sound joints were made in both types of material using both single and multi-run techniques. The improvement could not however be unambiguously attributed to joint design because the grain size of material in these tests was much finer than in the flake ingot material used earlier, and moreover no coarse-grained material was available, at this stage, for comparison.

Arc stability was much improved by comparison with that observed during butt welding, and there was only sporadic evidence of thermal etching. Sound welds were produced with welding current of between 60 and 80 amp, at a speed of about 6 in./min. A typical sound joint in pebble ingot is shown in Fig. 5, and the grain structure in and near the weld zone of a sample of rolled pressureless-sintered material is illustrated in Fig. 6. In spite of the coarse weld structure it was evident that grain growth in the parent metal adjacent to the weld was not excessive, and the relationship between weld and parent metal grain size as shown in the illustration was in fact typical of all other sheet and edge welds made during this investigation.

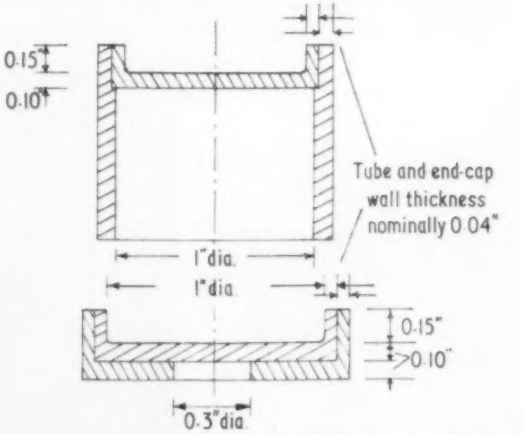
The depth of interfusion between edge welded specimens was invariably somewhat less than the total depth of fusion owing to the occurrence of a small amount of oxide at the root of the weld, which prevented proper coalescence. This is strictly analogous to the so-called 'root defect' that characterizes aluminium welds made by the tungsten-arc process, and was not considered to be a serious defect for the joint configuration in question.

Tube-End Cap Welding Trials

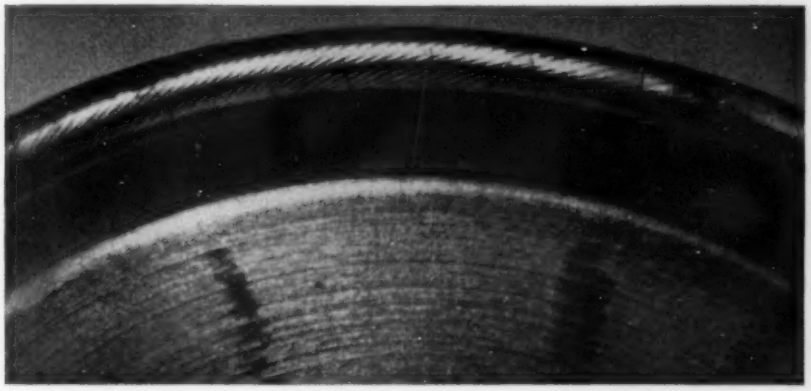
The comparative success achieved in edge welding prompted the making of a series of experimental welds aimed at examining the problems that might be encountered in producing end cap welds, typical of those employed in the manufacture of fuel elements. This exercise had an additional advantage in that material in rod and tube forms was more readily available than sheet and, moreover, specimens could be machined from comparatively small quantities of beryllium.

Tests on extruded flake ingot material

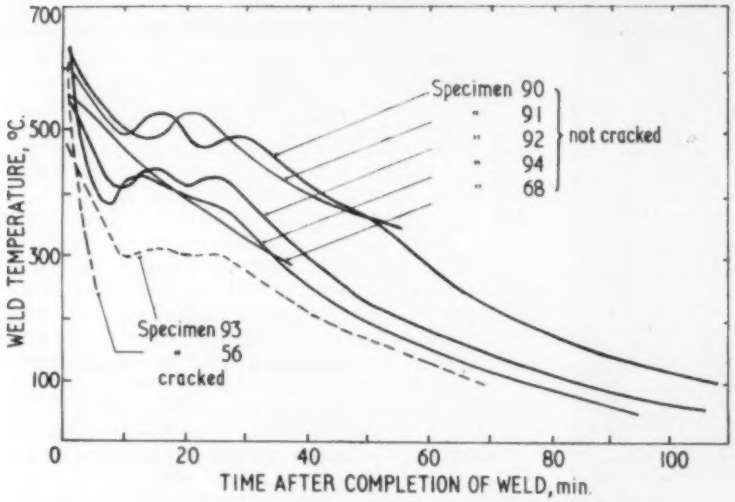
Preparation—Specimens were machined from hot extruded material to the configuration shown in Fig. 7*a*, the average grain size of the tube and rod being 100 and 50 microns respectively. Before welding, most specimens were swab degreased with acetone, although a few were chemically treated, some being brightened by immersion for 1 min at 100°C. in a solution of



7—*Specimen designs for tube-end cap welding:* (a) *Extruded ingot material;* (b) *pressureless sintered material*



8—*End cap weld in extruded flake ingot, showing transverse cracks (a.c., 95 amp, 36 in./min welding speed, not pre-heated)* ×8



9—*Cooling curves for single-run tube-end cap welds in extruded ingot material*

ortho-phosphoric acid (sp. gr. 1·25) containing 10% by volume of concentrated sulphuric acid and 130 g/litre of chromic acid, and others electro-polished for about 3 min in a cold solution of orthophosphoric acid (sp. gr. 1·25) containing 15% concentrated sulphuric acid, 15% glycerol and 15% alcohol (by volume) using a nickel cathode with an anodic current density of about 5 amp/sq.in.

Welding—It was evident from a few tests that good contact between the two parts of the joint was necessary to ensure consistent interfusion, and this condition was satisfied when the parts were a firm push fit. Radial clearances of up to 0·003 in. were generally satisfactory but clearances exceeding 0·005 in. resulted in erratic interfusion. End caps of exceptionally tight fit were unsatisfactory, as the tube frequently cracked during assembly before welding because of the poor room-temperature ductility of the material.

Welds were made using single and multi-run techniques with currents in the range 30 to 100 amp a.c. and welding speeds between 3 and 15 in./min. Longitudinal cracking was entirely absent in most specimens but transverse cracks occurred, primarily on the end cap side of the fused zone (Fig. 8). Single-run welds made at very low speeds contained longitudinal as well as small transverse cracks, and arc stability was generally so poor that pronounced thermal etching of grain boundaries occurred (Fig. 3). By contrast, a high-speed single-run procedure, although resulting in more extensive transverse cracking, as anticipated, gave much superior results with uniform fusion and freedom from grain boundary etching (Fig. 8). To examine the possibility that residual stress in the material was responsible for the cracking, some machined specimens were vacuum annealed for 1 hr at 800°C., chemically brightened and then welded. This treatment did not in any way decrease the extent of cracking observed.

An examination of results at this stage showed that least cracking occurred in multi-run welds. Since there was little difference in the extent of fusion it was inferred that the decreased cracking was due to differences in the thermal conditions. Equipment was therefore constructed to enable pre- and post-heating procedures to be studied. Welding tests on end cap assemblies were carried out at speeds ranging from 3 to 15 in./min, using the small tubular furnace illustrated in Fig. 2. Results demonstrated that whilst preheating in the range 400°–600°C. did not eliminate transverse cracking, supplementary heating, applied after welding to reduce cooling rates, enabled crack-free joints to be made. Grain boundary thermal

Table III

Welding conditions for slowly-cooled specimens (Fig. 9)

Specimen No.	*Tube Wall Thickness, in.*	*End Cap Wall Thickness, in.*	*Preparation for Welding*	*Diameter of Thoriated Tungsten Electrode, in.*	*Arc Length, in.*	*Argon Flow rate, cu.ft/hr*	*Preheat Temp., °C.*	*Welding Current, amp*	*Welding Speed, in./min*
56	0·040	0·040	Degreased	0·063	0·188	15	400	25	1
68	0·040	0·030	Degreased	0·093	0·188	15	500	60	15
90	0·045	0·040	Degreased	0·093	0·188	15	500	65	15
91	0·040	0·040	Degreased	0·093	0·188	15	500	65	15
92	0·040	0·030	Degreased	0·093	0·188	15	400	65	15
94	0·045	0·035	Degreased	0·063	0·188	15	400	30	3
93	0·045	0·035	Degreased	0·093	0·188	15	300	75	15

Table IV

Vacuum leak tests on welded tube-end cap assemblies in extruded flake ingot

Specimen	*Period under Vacuum Before Test, hr*	*Minimum Pressure Before Test*	*Pressure after Isolation from Pumps for 5 min, microns*	*Hydrogen Leak Test*	*Visual Appearance*
Solid brass cap waxed into specimen holder	1½	Below zero on Pirani scale (< 10^{-4} mm)	1·0, 0·9 — 0·95	No leak	—
Weld No. 90	1	Below zero on Pirani scale (< 10^{-4} mm)	1·4, 1·5 — 1·45	No leak	Sound
Weld No. 91	1	Below zero on Pirani scale < (10^{-4} mm)	1·0, 1·1 — 1·05	No leak	Sound
Weld No. 94	1	Below zero on Pirani scale (< 10^{-4} mm)	1·9, 2·1 — 2·0	No leak	Sound
Weld No. 95	1	0·3 microns	Atmospheric	Pronounced leak	One transverse crack in weld
Weld No. 92	1	150 microns	Atmospheric	Pronounced leak	Sound weld. Cracks in tube (present before welding)
Weld No. 93	1	180 microns	Atmospheric	Pronounced leak	Transverse cracks in weld

etching was still evident at a welding speed of 15 in./min, but this proved to be of no significance and was easily removed by a light electro-polishing treatment.

Further tests were made in which, after welding at a particular preheat temperature, each specimen was cooled to a lower temperature, homogenized for 15 min, and then slowly cooled to room temperature. Cooling curves were constructed (Fig. 9), and when compared with results of continuous cooling experiments, indicated that for the type of weld examined transverse cracking probably occurs in the temperature range 300°–400°C. and is independent of welding speed within the range 3–15 in./min. A summary of welding conditions employed for these particular tests is given in Table III.

Metallography—Effective depth of interfusion in all single-run welds was between 0·025 and 0·040 in., the thickness of each welded edge being about 0·04 in. On the other hand multi-run welds made at low speeds fractured on being machined before metallographic study, and were evidently not effectively joined. Metallographic examination of specimens representing all the welding conditions employed indicated that there was no serious defect other than the transverse cracking already described.

10—*End cap weld in pressureless sintered material* ×3

Leak Tests—Vacuum leak tests were carried out on selected welds representing cracked and visually sound specimens. Each specimen was degreased in acetone and sealed with picene vacuum wax into a jig with a

machined annular groove. The jig was attached to a standard 3 in. diffusion unit and pumped for a minimum period of one hour. Each specimen was tested initially by isolating it from the pump and observing the leak rate of the assembly on a Pirani gauge; results were compared with those from a machined brass blank tested in the same way. To determine whether observed pressure increases were due to leaking or out-gassing, checks were made using a hydrogen probe leak test unit, with a Pirani gauge and sensitive galvanometer. Results listed in Table IV indicate that visually sound welds did not leak under a vacuum of 10^{-4}–10^{-5} mm Hg, whereas specimens containing a small number of visible cracks and, in one instance, only one crack exhibited a pronounced leak when tested by either the leak rate method or by the hydrogen probe technique.

Tests on pressureless sintered material

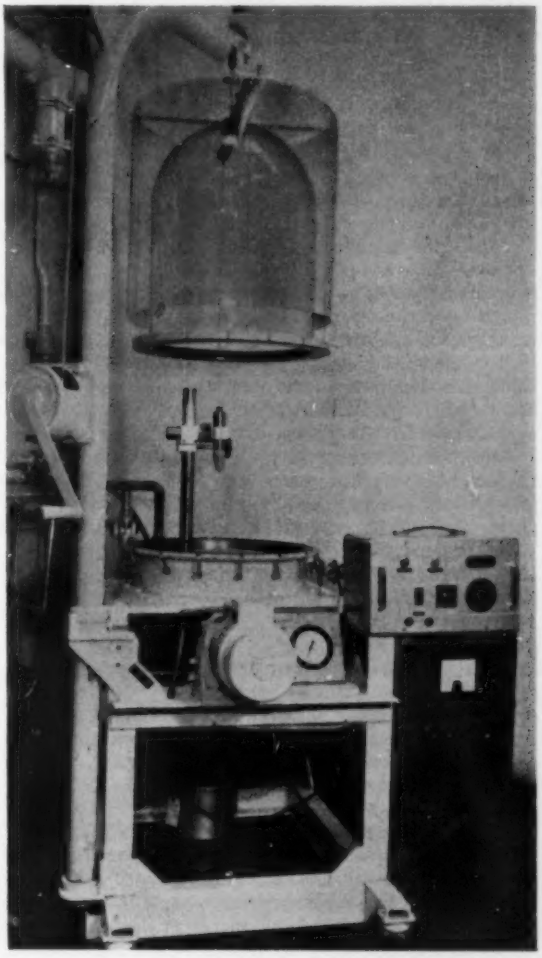
A limited number of specimens with grain size 25 microns, was machined from bar to the configuration shown in Fig. 7*b*, and tests were carried out over as wide a range of welding conditions as possible. All samples were electro-polished before welding, since experience had indicated that a degreasing operation alone before welding produced joints of rather dirty surface appearance. The influence of pre- and post-heating practices was also studied.

Results indicated that the cracking susceptibility of welds in pressureless sintered material is lower than that of extruded ingot. For example, at a welding speed of 15 in./min, weld cracking could be avoided by preheating to, and slowly cooling from, 100°C. compared with a minimum temperature of 400°C. for extruded ingot welded at the same speed. In fact one specimen welded at 9 in./min without either preheating or slow cooling was found to be entirely free from cracks (Fig. 10). Metallographic examination revealed slight fine porosity and entrapped beryllia in all welds, but these features were never more pronounced than in the parent material, which normally contains about 0·5% beryllia. One interesting feature of weld sections in this material was the comparatively low level of porosity and oxide present in the upper half of the fused zone.

Tests in a Controlled Atmosphere Welding Chamber

The quality of the welding atmosphere was not good in the glove-box used for the work described so far, as evidenced by the failure to detect any difference between welding characteristics using commercial and high-purity argon for shielding. A glass welding chamber equipped with vacuum pumps and capable of maintaining an atmosphere of pure argon was therefore constructed, and crack-free edge welds have been made between tubes and end caps machined from extruded flake ingot beryllium, without preheating or deliberate slow-cooling, using a mechanized tungsten-arc procedure with alternating current. A general view of the apparatus is illustrated in Fig. 11.

In tests carried out so far, the chamber was evacuated to 10^{-3}mm Hg and flushed to yield an argon atmosphere of 99·995% purity, no argon being admitted during welding. Equally satisfactory results have been obtained at pressures in the range 200–700 mm Hg, but arc stability rapidly deteriorates as pressure is reduced below 200 mm.



11—*Apparatus for welding in controlled atmospheres*

Initial results suggest that freedom from cracking may be attributable to the lower rate of cooling in the static argon atmosphere. Further work is being carried out to assess the influence of shielding gas purity.

Discussion

Despite the limited scope of the welding exercise discussed, several important points have emerged. work has shown that the most satisfactory conditions for fusion welding beryllium arise when a.c. or electrode positive d.c. is used. This result is in accordance with experience with inert-gas arc welding as applied to aluminium and magnesium, where the influence of arc polarity on oxide dispersal is well known.

Two distinct forms of cracking have been noted, although the temperature at which these occur has not been precisely defined. Visual observation during

welding indicates that longitudinal hot cracking occurs at or near the solidus temperature, and the fact that welding speed tends to reduce longitudinal hot cracking is in line with predictions that can be drawn from Moore's work on hot cracking in aluminium alloys.[9] The elimination of transverse cracking by slow cooling in the temperature range 200°–400°C. may be related to the achievement of stress dissipation in this range, where beryllium is known to exhibit maximum ductility.

The beneficial effect of small-grain size in minimizing cracking susceptibility is clearly indicated. Again, this result for hot (super solidus) cracking can be predicted from theory, but the effect of grain size on low-temperature cracking is less clearly understood. It may well be that material comprised of randomly orientated fine grains is more ductile at all temperatures than a coarse-grained structure, and is therefore more able to contain the imposed strains without cracking.

Joint configuration exerts considerable influence on the extent of cracking, edge welds being considerably less subject to longitudinal cracking than butt welds in sheet. Similarly, edge welds in sheet are less subject to transverse cracking than end cap welds. The cracks in this latter type of joint occurred on the inside edge of the fused zones, behaviour which is consistent with the residual stress pattern likely to arise in joints of this configuration.

Insufficient systematic work has been done to enable a detailed comparison to be drawn between the welding properties of various grades of wrought beryllium, but the indications are that the products manufactured by powder metallurgical methods are superior to those processed directly from cast ingot, if only by virtue of their smaller grain size.

It is appreciated that a full appraisal of the quality of tungsten-arc welds in beryllium will require the determination of mechanical properties of joints and this work, currently being carried out, will be reported in detail in due course.

Conclusions

(1) Satisfactory tungsten-arc welding of beryllium can be achieved when either a.c. or d.c. with electrode positive is used.

(2) Two forms of cracking occur in beryllium: longitudinal cracking, which occurs at or near the solidus temperature, and transverse cracking, which occurs at temperatures below approximately 400°C. Longitudinal cracking is reduced when the welding speed is increased and is less serious in fine-grained material. Transverse cracks can be eliminated by slow cooling from a temperature above 400°C. This may be achieved either by employing auxiliary heating or by controlling the heat input in making the joint.

(3) Beryllium fabricated by powder metallurgy methods has, by virtue of its smaller grain size, better properties from the welding viewpoint than material processed directly from cast ingot.

(4) Use of a welding chamber capable of maintaining a controlled static atmosphere of high-purity argon has established that sound welds can be produced, without preheating or deliberate slow cooling, by use of an a.c. tungsten-arc technique.

Acknowledgments

The authors wish to record their thanks to Mr. C. A. Terry and Dr. T. W. Farthing of I.C.I. Ltd. for helpful discussion. Also to Mr. G. C. Ellis, Superintendent of Research Metallurgy at A.W.R.E., for his constant interest and encouragement, and to the Director, Atomic Weapons Research Establishment for permission to publish this paper.

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A Note on the Relationship between Chemical Composition and Hot-Cracking in Mild and Alloy Steels

By W. K. B. Marshall,
B.ENG., F.I.M.

In an earlier paper the author offered an explanation of the effect of various elements in promoting or combating hot-cracking in fully austenitic weld metals. In the present note he shows how the explanation can be extended to cover hot-cracking occurring in ferritic welds. Certain elements are classified as primary crack formers (e.g., *sulphur, phosphorus and silicon*), *whilst the effect of other elements depends on whether they favour the presence of ferrite or of austenite in the early stages of solidification; those which encourage austenite formation increase the tendency to hot-cracking, whilst those which encourage ferrite formation reduce it. This, the author suggests, is connected with the solubility of the various elements in austenite and ferrite respectively.*

ALTHOUGH hot-cracking is no longer a problem of any significance in welding mild steel it is still a serious nuisance with fully austenitic steel, and recent papers have shown that it is likely to be one of the more intractable problems in welding high-tensile, low-alloy steels. It is thus of rather more than academic interest to be able to build up a picture which, with respect to hot-cracking, explains the behaviour of these various materials.

There are obviously many elements that can cause hot-cracking. This is becoming abundantly clear from recent literature, particularly that published in Russia.[1] However, apart from the special effect of niobium, the cracking with the most serious consequence industrially does not appear to be associated with the presence of unusual elements but rather with particular proportions of the more common elements and impurities. This has already been pointed out by the present author,[2] in an attempt to explain the effects of chemical composition and metallurgical constitution on the hot-cracking of a variety of austenitic weld metals. It was suggested then that the explanation might be extended to include carbon and low-alloy steels, but there did not appear to be sufficient practical data to enable this to be done in any detail. Recently, however, more data have become available which appear to show in quite a striking way that this extension is possible, thus providing an explanation of the hot cracking of ferrous materials in general. At the same time, a re-examination of the alloy constitutional data given in the earlier paper suggests that certain extrapolations made at that time require qualification, and it is a purpose of this note to make these qualifications and to show how the new data fit the general theory.

In the earlier paper, the author invoked an accepted theory of hot-cracking based primarily on the work carried out at Birmingham University on aluminium alloys, and showed how this was consistent with the effect of composition and constitution on the cracking of Cr–Ni and high-manganese austenitic weld metals. The Birmingham work demonstrated that there is a quantitative relationship between the extent of hot-cracking and the temperature interval between liquidus and solidus. The present author pointed out that the three elements—sulphur, phosphorus, and silicon—present in ferrous alloys give systems showing a wide solidification range and thus theoretically can be responsible for hot-cracking. It was postulated that sulphur always contributes towards cracking, but whether or not phosphorus and silicon contribute depends on the proportions of austenite and delta ferrite present early in the solidification process. If solidification is primarily as austenite as, for example, in fully austenitic Cr–Ni or high-manganese steels, silicon, and especially phosphorus, play a part. If it is as ferrite, such as in mild steel and high-chromium irons, phosphorus and silicon will not contribute materially. It was suggested that this can be explained by reference to the solubility of the elements in austenite and ferrite respectively, and to the temperature interval between the liquidus and solidus in the corresponding quasi-binary systems. In the absence of more direct data, the binary systems involving sulphur, phosphorus, and silicon on the one hand and iron and nickel on the other were used to deduce the probable behaviour in systems between the elements and ferrite and austenite respectively.

The foregoing conception was used to explain the relative immunity to hot-cracking of Cr–Ni steel weld metals containing mixed ferrite and austenite, and the notorious sensitivity of weld metals of similar impurity content but fully austenitic in structure. The suggestion was also made that the hot-cracking experienced in high-carbon ferritic weld metals may not be caused directly by the high carbon content but by the fact that solidification in such weld metals is in the form of austenite.

Re-examination of the constitutional diagrams, C–Fe–P, and C–Ni–P however suggests that, although

Manuscript received 23rd November 1959.
Mr. Marshall is Chief Metallurgist of Rockweld Ltd.

increase in carbon or nickel or both reduces the solubility of the phosphorus, there is not an immediate drop to very low solubilities when the alloy content is such as to make the primary solidification austenitic. The effect is more gradual but it is sufficiently marked to be consistent with the explanation offered.

Recent Work

The results of recent work reported by Wilkinson, Cottrell, and Huxley[3] support the foregoing conception of the role of austenite and ferrite.

These authors found that hot-cracking in the weld metal and at the sides of argonarc welds in various high-tensile steels increases with increase in sulphur, phosphorus, carbon, silicon, and nickel content, and decreases with increase in manganese, molybdenum, chromium, and vanadium content. They offered an empirical formula in which cracking is proportional to:

$$C\left\{\frac{S+P+\frac{Si}{25}+\frac{Ni}{100}}{3\,Mn+Cr+Mo+V}\right\}$$

From this it will be seen that the elements causing cracking are either those which might be called the primary crack formers—sulphur, phosphorus, and silicon—or those favouring the formation of austenite during solidification. Those elements which help to suppress cracking are (with the exception of Mn) ones which favour solidification as ferrite. It should be noted that the steels examined by Wilkinson, Cottrell, and Huxley contained appreciable amounts of carbon and therefore had a good deal of austenite present during early solidification. It is suggested that this is why the phosphorus and silicon contribute to crack formation.

It is interesting to note that these authors found that 12% Cr steel, although containing, by their standards, considerable quantities of carbon, silicon, phosphorus, and sulphur, did not crack. This is explained on the present theory by the fact that the material solidifies as 100% ferrite and thus silicon and phosphorus would not operate as crack-formers.

Sopher in America[4] provides more data concerning the effect of sulphur, phosphorus, and carbon on the hot-cracking of welds in Ni–Cr–Mo steels. He shows that in steels with about 2% Ni, 1% Cr, 0·3% Mo and 0·2%–0·6% C, the effects of sulphur and phosphorus on hot-cracking are about equal. With sulphur and phosphorus each less than 0·010%, increase in carbon from 0·20% to 0·59% gives some increase in cracking, but the effect is not as great as that due to sulphur and phosphorus. This relatively mild effect of carbon is not unexpected since at the lowest carbon level investigated (0·20%) the metal on solidification would already be predominantly in the form of austenite, and increase in carbon content would not, therefore, have the same marked effect as it would if lower carbon contents had been investigated. Moreover, the phosphorus contents were low and therefore on the present theory, even when this element was induced (by the increase in carbon) to act more strongly as a crack-promoter, the effect would not be marked.

Another paper that reports results that are consistent with the theory under consideration is that by Padgaetskii[5] on the effect of various elements on the hot-cracking of submerged-arc welds. He showed that hot-cracking increases markedly with increase in carbon and sulphur content. The effect of sulphur can be combated by increase in manganese but, as the carbon increases, the Mn/S ratio required to suppress cracking increases also. Above about 0·16% carbon, however, further increase in the Mn/S ratio is ineffective, and in the particular test employed all such weld metals invariably cracked.

Padgaetskii's results may be explained on the grounds that below 0·15% C sulphur is the only primary cracking agent operating, and this may be combated by manganese additions. As the carbon increases, the amount of austenite formed during solidification increases, thus enabling phosphorus to become more active as a primary cracking agent. Above about 0·16% C there is so much austenite formed on solidification that phosphorus takes over as the principal cracking agent, and further increase in manganese is then of no avail because it is unable to combat the cracking caused by this element.

A recent paper by Jones[6] reporting work carried out at the B.W.R.A. confirms the effect of C, S, Mn, Ni, and Cr in metal-arc welding. The influence of the Mn/S ratio and its relation to the carbon content agrees with Padgaetskii's results, and the harmful effect of Ni and beneficial effect of Cr are also confirmed.

This general conception of the cause of weld cracking thus appears to be consistent with the new data, and there is perhaps, therefore, some justification for attempting a more detailed examination of how it applies in different circumstances. This is done in the following, where data from both ferritic/martensitic and austenitic weld metals are used.

Effect of Sulphur, Phosphorus, and Silicon

It is interesting to compare the results of Wilkinson, Cottrell, and Huxley's work on ferritic/martensitic steels with the experience of Hoerl and Moore[7] on fully austenitic 18/13/1% Nb steels. In a statistical study, they found that the extent of hot fissuring and cracking was proportional to $P+\frac{S}{6{\cdot}5}+\frac{Si}{1250}$. The corresponding expression from Wilkinson, Cottrell, and Huxley's paper is $P+S+\frac{Si}{25}$. Equal rating of phosphorus and sulphur in low-alloy steels is supported by Sopher's results, but it would be interesting to know whether in higher carbon steels, (*i.e.*, those solidifying more strongly as austenite) phosphorus would become the more dangerous crack-promoter as it is in fully austenitic materials. The effect of silicon is discussed later.

Effect of Carbon, Nickel, and Manganese

The binary diagrams Fe–C, Fe–Ni, and Fe–Mn are very similar in the neighbourhood of the liquidus at the iron end of the diagrams. If the tendency of C, Ni, and Mn to form austenite on solidification is assessed on the basis of the peritectic composition, then the potencies of the three elements are:

$$C=1;\ Ni=\tfrac{1}{2\cdot5};\ Mn=\tfrac{1}{4\cdot0}.$$

Wilkinson, Cottrell, and Huxley give a factor for Ni of $\frac{1}{100}$ although Rollason and Roberts[9] imply that its effect might be greater than this. It is also reported that in practice 3½% Ni steels give more cracking

troubles than other low-alloy steels, particularly in submerged-arc welding.

As will be noted later, the effect of manganese is rather a special one, in view of its association with sulphur. Moreover, Sloman and Rooney[8] have shown that in many weld deposits a great deal of it is tied up in association with oxygen and silicon, so that it is difficult to assess its effect as an austenite former. Making the arbitrary assumption that half the amount present is available to form austenite, then the normal manganese content of ferritic weld metal (0·5–1·0%) has a carbon equivalent (based on the factors just quoted) of 0·006–0·012%; *i.e.*, it does not contribute materially to the formation of austenite in such weld metals. Nickel, on the other hand, can be significant; Rollason and Roberts[9] showed that 0·6% Ni had a detectable effect on hot-cracking. This nickel content would be equivalent to 0·024% C, which also would have a detectable effect. A 3½% Ni steel has a carbon equivalent of 0·14%, and this could have a very serious effect on cracking.

American work has shown that in fully austenitic Cr–Ni steels, increase in carbon content has a beneficial effect on hot-cracking. The reason for this is in no way associated with the present discussion, but it would be interesting to know whether, with low-alloy steels also, increase in carbon content might be shown ultimately to reduce hot-cracking. This must be so, since cast-irons, in spite of their large amounts of S and P do not readily produce hot cracks. The practical difficulty, of course, is that with increase in carbon, the weld metal becomes increasingly hard, and cold-cracking then becomes the major problem.

It is interesting to note in passing that the foregoing factors, deduced from the constitutional diagrams for carbon, nickel and manganese, show a striking agreement with the factors of 1, $\frac{1}{30}$, $\frac{1}{60}$ found empirically by Schaeffler[10] to represent the potency of the respective elements in producing austenite in Cr–Ni austenitic weld metal.

Special Effect of Manganese

As previously noted, manganese has a dual role, but there is little doubt that in ferritic weld metal its specific effect of immobilizing the sulphur as MnS is the more important one. In fully austenitic steels, however, and presumably in others that solidify as austenite, and thus where phosphorus and silicon are operating as crack formers, its effect is less spectacular since it cannot combat the effect of these latter two elements, although presumably it still combats the effect of sulphur. It would be interesting, incidentally, to determine at what point manganese additions to ferritic steels cease to improve crack resistance and begin to cause cracking owing to the effect of the element in promoting solidification as austenite. Certainly in the high-manganese steels of the Hadfield type, hot-cracking is a serious nuisance if phosphorus is present in more than small amounts.

Effect of Chromium, Molybdenum, and Other Ferrite Formers

Wilkinson, Cottrell, and Huxley rate Cr and Mo as equal in their tendency to suppress hot-cracking. Schaeffler also rates them equally as ferrite formers, and, moreover, he assesses the potency of these two elements as suppressors of austenite about equal to the potency of nickel as a promoter of austenite. It is difficult to determine from the results of Wilkinson, Cottrell, and Huxley how they relate Ni and Cr, but it would be interesting to know whether, in fact, the effects are about equal and opposite, and also whether the other ferrite formers (W, Nb, Ti) are effective in combating cracking.

Dual Effect of Silicon

There is no doubt that in materials which solidify as austenite, silicon is a mild crack-promoter. This is partly because it satisfies the requirement of giving a low-melting-point eutectic with limited solid solubility with austenitic materials, but it is also possible that its ability to combine with other elements to give low-melting-point silicides is also contributary.

On the other hand, silicon is a ferrite former, so that its effect as a crack-promoter might be expected to increase up to a certain point and then to diminish as primary solidification becomes more and more ferritic. This certainly happens with Cr–Ni alloys which are originally just in the austenitic zone. An increase in silicon content first increases hot-cracking and then, as the material becomes partially ferritic, reduces hot-cracking.

Conclusions

If the foregoing hypothesis is broadly correct, a way is clear towards rationalizing the control of cracking in low-alloy steel weld metals. For instance, if the carbon and nickel are kept low, it is possible that phosphorus and silicon can be tolerated above the present safe limits. The same may be achieved with a reasonable carbon content if sufficient ferrite formers are introduced to ensure ferrite in the primary solidification. The effect of silicon in this direction might be worth investigating.

On the other hand, it follows that if the phosphorus is kept to a very low figure, carbon and nickel may be tolerated up to quite high amounts. It is possible that sulphur is not so important as suspected in this connection.

In many instances, the simple mechanism described clearly does not apply. But it does seem to provide some explanation of the behaviour of the more common elements occurring in most steels, and it will be interesting to see how consistent it is with the new data now coming forward.

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INTERNATIONAL INSTITUTE OF WELDING

Reports of Commissions – 1959

Abridged versions of the Chairmen's reports for eight Commissions of the IIW are given below. These review the activities of the Commissions following the Annual Assembly held at Opatija, Yugoslavia, in June 1959. Reports of Commissions III, VIII and XIII were published in the December 1959 issue of B.W.J.

Copies of the complete authorized reports may be obtained from the Technical Secretariat, International Institute of Welding, 32 Boulevard de la Chapelle, Paris XVIIIe.

Commission I: GAS WELDING AND ALLIED PROCESSES

Chairman – Dr. C. G. Keel (Switzerland)

Brazing and Surfacing

The Commission has approved for publication and submission to ISO two draft codes of symbols for filler metals. The first (document I–108–59) deals with filler metals for gas surfacing, and relates to the type of metal and alloy, the form of the filler metal, the special characteristics of the deposited metal and properties which are of importance from the point of view of the method used. The second document (I–110–59) concerns the symbolization of filler metals for braze welding, and makes it possible to designate the type of metal or alloy to which the filler metal belongs, the characteristics of the deposited metal and the conventional bond strength of the filler metal on mild steel, cast iron or other metals.

Oxygen Cutting

In a report (I B–213–58) on the fatigue strength of powder-cut chromium steel specimens, a comparison was made between the behaviour of brushed or polished and mechanically machined surfaces. The tests showed that oxygen-cut surfaces have a greatly reduced strength under alternating bend stresses, by comparison with mechanically machined surfaces.

A list (I–112–59) of oxygen cutting terms in three languages, has been submitted to Commission VI (Terminology) as a contribution to the Multilingual Collection of Terms.

Metal Spraying

A first list of terms on metallization has been submitted to Commission VI.

Definition of Welding Procedures

Working Group ID has compared the gas welding procedures used in various countries (Doc. ID–402–59). The Group will continue its activity by trying to collect information on the methods of oxy-acetylene welding used for non-ferrous metals and for plastics.

New Activities

The Commission has set up a working group (E) to study oxy-acetylene pressure welding, and a working group (F) to examine technical questions relating to gas welding equipment; in the first place a study of blowpipes and their different uses.

Commission II: ARC WELDING

Chairman – Prof. ir. H. E. Jaeger (Netherlands)

Hydrogen in Weld Metal

Sub-commission A is continuing the work on improving the ISO code of symbols for electrodes, particularly in relation to low-hydrogen types.

Other work has included investigations on the influence of hydrogen and microfissures on the impact and fatigue strength of weld metal, which show that microfissures are present and justify a lowering of the fatigue limits, and on the effect of very fine inclusions on the formation of halos.

Testing and Measurement of Arc Welding Equipment

Sub-commission B has covered a wide field of study. Work is continuing to define coefficients for the suitability for welding of various types of equipment. Attempts are being made to improve the characteristics of certain generators and rectifiers so as to reduce the variation in penetration obtained. The suitability of single-phase transformers for welding is also being studied. There has been confirmation of earlier observations of a lack of stability in electronic apparatus for measuring arc welding currents and voltages.

The flexibility and permissible current densities in welding cables are also being studied, the latter at the request of IEC, and the Sub-commission is collaborating with Commission VIII in the preparation of the manual on health and safety in welding.

Testing and Measurement of Weld Metal

Sub-commission C has dealt with methods of determining the mechanical properties of weld deposits from deep penetration electrodes, hot-crack testing of austenitic electrodes, impact tests for weld metal (recommending that only Charpy V-notch impact values shall be appended to the ISO Code of Symbols for Electrodes), and acceptance tests for electrodes for welding low-carbon and low-alloy high-tensile steels. Doc. II–64–59, which describes methods of carrying out these acceptance tests, proposes the classification of electrodes by a scale of mechanical

properties, similar to that for steels, without taking into account the type of coating.

Deep-penetration Welding

A code of good practice to facilitate the application of this technique is to be prepared.

Classification of Electrodes

Earlier drafts have been amended in collaboration with other interested Commissions, and work will continue on symbols for electrodes for building-up and for the welding of castings.

Productivity

In view of the limited amount of information available relating specifically to welding, the working group on this subject is finding difficulty in obtaining precise data. It will nevertheless continue its studies, particularly in relation to arc welding and the fusion efficiency of covered electrodes.

Commission IV: DOCUMENTATION

Chairman – Mlle L. Blosset (France)

Bibliographical Bulletin for Welding

The Bulletin continues to be produced as a result of the permanent collaboration of the French publishers and of periodic contributions from some Commission members. The French organizations still maintain the burden of producing the largest contribution, and are responsible for the translations of abstracts to and from English and French.

The deficit on publication for 1958, borne by the French Institute of Welding, is gradually decreasing each year, due partly to increased advertising revenue and partly to fees and royalties payable for the use of abstracts.

Literature Classification

Attempts are continuing, in collaboration with Commission IX, to establish a criterion of differentiation between high- and low-alloy steels for the purposes of classification.

The Commission has recommended the publication of Doc. IV–93–59, which is a concordance between the UDC and IIW systems of classification. This will be published, possibly under both UDC and IIW headings, by the International Federation of Documentation.

Exhibitions

The Commission was again concerned in the exhibition of publications at the Opatija Annual Assembly, organized by the Yugoslavian delegation. In addition, for the first time, there was an exhibition of photographs of welded construction and the application of allied processes. This is to be repeated, with new features, at each future Assembly.

Commission V: TESTING, MEASUREMENT AND CONTROL OF WELDS

Chairman – Professor G. A. Homès (Belgium)

The Commission has suffered a sad loss in the sudden death of its Vice-Chairman, Mr. L. van Ouwerkerk who was also Chairman of Sub-commission A (Radiography).

Radiography

A draft booklet of 26 radiographs of typical weld defects in mild or low-alloy steels, together with macrographs and drawings, has been recommended for publication.

Work is continuing on bringing up-to-date the collection of Weld Reference Radiographs and on studies of calibration of X-ray equipment, acceptability of defects in pressure vessels, and characteristics of radiographic films.

There has been discussion on the values of image quality to be recommended to Commission XI for the radiography of pressure vessels, and in connection with the use of IQI recommended by the IIW.

Considerable work has been done on the radiography of light alloys, and about 100 radiographs are to be included in a proposed collection illustrating typical defects. A report (IIS/IIW–35–59) on recommended practice for inspection of up to 2 in. thick Al and Mg alloys has been released for publication.

The final English and French texts of the Handbook on radiographic apparatus and techniques (Doc. IIS/IIW–46–60) have been circulated to member societies.

Ultrasonic Inspection

A list of terms used in ultrasonic testing has been published and so has a report on reference blocks. A report on equipment for and methods of ultrasonic testing is nearing completion. Further work will be devoted to response curves of typical weld defects, inspection of light alloys and inspection of brazed tools, fillet welds, and welds on stainless and clad steels.

Destructive Testing

There is still more work to be done to complete the atlas of methods of mechanical testing, but about 50 illustrations and corresponding text have been assembled. Mechanical tests for light alloy welds are also being studied.

Non-destructive Testing

Sub-commission E has examined a series of practical problems in weld inspection to see which was the best method of solving them. It was agreed that the inspection of welds on austenitic steel, stainless clad steel, and spot welds should preferably be carried out by radiography, but that to detect surface defects in welds on austenitic steel, penetrant testing methods are more suitable. Ultrasonic inspection should preferably be used for fillet welds and may also be used for spot welds.

The inspection of T-joints can easily be carried out by ultrasonics provided that the thickness is not too small, but magnetic means can sometimes also be used.

The inspection of welds in pipes of small diameter and small wall thickness may be carried out either magnetically or by ultrasonics. However, lack of fusion due to a layer of oxide can never be detected.

Welds on Plastics

Following the earlier collection of information on

the inspection of welds on plastics, the Commission has continued its research and has developed a technique of ultrasonic inspection by an echo method, using single probes.

Mechanical tests have previously been of little value because of the scatter of results, but it is considered that a fundamental study of the mechanism of deformation and fracture would make such tests more useful. Research is to be started in Belgium, where also investigations have been made on the weldability of polythene, p.v.c., and other plastics. This research has already led to an improvement in the strength of butt welds to almost that of the base materials.

Commission VI: TERMINOLOGY

Chairman – F. M. L. van Horenbeeck (Belgium)

The Commission is preparing, for the Multilingual Collection of Terms, the section on resistance welding; this will contain terms in the same 12 languages as were included in the first three sections, and also in Polish, Russian, Slovak, and Turkish.

A multilingual section on terms relating specifically to oxygen cutting and other allied cutting processes is planned for 1963 or 1964; a section devoted to terms used in metal spraying, surface hardening, and other allied processes will appear about 1966, and a section relating to brazing and braze welding probably during 1968.

Commission VII: STANDARDIZATION

Chairman – A. Leroy (France)

The Commission continues to co-ordinate the work of other Commissions so far as they concern standardization, and acts as liaison between the IIW and the ISO as well as collaborating with other international bodies concerned with standards.

In particular, the Commission has actively co-ordinated the work of Commissions I, II and XII in relation to symbolization of filler metals and electrodes and has submitted recommendations to ISO/TC 44. The work of Commission III on the grading of spot welds in terms of quality is being followed carefully with a view to transmitting the results to the ISO.

In other fields the Commission has studied a document on welded connections for pressure vessels, resulting from the collaboration of Commissions XII and XV and has recommended that it should be submitted to ISO/TC11, dealing with the unification of boiler codes. Recommendations for the choice and classification of steels for use in welded structures have been passed to the European Coal and Steel Community.

Members of the Commission have attended, as observers, a number of ISO/TC44 Sub-committees. Recommendations of Commission II that the symbolization of electrodes should relate to the fundamental positions have been adopted, and assistance is to be given in defining welding positions for pipelines. Other IIW Commissions have been informed of ISO Sub-committee work on design for welding, arc and resistance welding equipment, and of IEC work on health and safety.

Lists of national welding standards, prepared from information received from twelve countries, are to be amplified annually, and are to be sent to all member societies.

Commission IX: BEHAVIOUR OF METALS SUBJECTED TO WELDING

Chairman – Prof. K. Rühl (Germany)

Houdremont Lecture

Prof. Bastien (France) gave a lecture in memory of Prof. Houdremont (Germany): "Hydrogen in welding – A comparison between the behaviour of welded, cast or wrought steels". (This is to be published in the August *B.W.J.*)

Brittle Fracture

A bibliographical report has been prepared, on articles published on this subject during the past twelve months. With the need to obtain data on service failures documents have been prepared for publication, with the aim of providing guidance on the form in which the material should be reported and the data required for investigating failures involving brittle fracture. Papers on fracture mechanics were also received for publication.

Weldability

Data is to be collected and published on continuous cooling transformation curves for weldable steels, and a report is to be prepared on the CTS weldability test. There is also to be a comparative study of other testing techniques and a catalogue of weldability tests is to be prepared. A Sub-commission is to attempt to define the "heat-affected zone" and is to study the compatibility of various types of electrode with different steels.

A working group has been set up to deal with problems concerned with the welding of light alloys and other non-ferrous metals.

A report on the classification of steel structures has been passed to Commission XV. It emphasizes the need, now that recommendations concerning different grades of steel have been approved, of presenting recommendations that would help the engineer to determine the most suitable grade of steel for a particular structure.

Commission X: RESIDUAL STRESSES AND STRESS RELIEVING

Chairman – Dr. R. Weck (United Kingdom)

Light Alloys

Although medium strength aluminium alloys at present used in welded construction are not liable to brittle fracture at lower temperatures, the Commission has decided to carry out enquiries into any problems which have arisen in the field of light alloy construction and which are attributed to the presence of residual stresses, due to welding.

Residual Stresses

A brief statement by the Soviet delegation, outlining the views of Soviet experts on the effects of residual

stresses, has been accepted as corresponding with the views of the Commission as a whole, and it has been recommended for publication. (See below.)

Reports on residual stress measurements that have been submitted include tests on the effect of service stresses over a period of years, measured on one ship, records of stresses produced by joining two halves of a prefabricated ship, and measurements of stresses in electroslag welds. These latter indicate that surface stresses on both sides of a plate are compressive.

Fatigue tests on submerged-arc butt welds have shown that stress-relief has little effect on the fatigue limit of the welded test pieces, although the parent metal strength is substantially reduced. Several reports on the effects of residual stress on brittle fracture have been considered. Tests on spherical containers with artificial defects indicated that mechanical or thermal stress relief did not reduce the tendency to brittle failure but did raise the strength at failure to near the yield point. Further tests show that mechanical tensile stress relief is not effective until complete yielding is obtained. Thermal stress relief below 420°C. is also not fully effective in preventing low stress brittle fracture. The fracture transition temperature in the heat-affected zone of welds appears to be about 10°C. lower than that of the weld and parent material.

Stress Relieving

A report is to be published dealing with the stress relaxation, as a function of time and temperature, of a number of different alloy steels. But further co-operative work is to be carried out to ascertain whether the data obtained from simple torsion tests can be applied also in practice.

Effects of Stresses due to Welding

Commission X – "Residual Stresses and Stress Relieving"

(1) Residual stresses* have no influence on the ultimate strength of a given member if the material is in a ductile state, and works under a static or an impact load. It is, however, recognized that plastic deformation may occur in isolated zones at lower loads than it would have done in the absence of residual stresses.

(2) The residual stresses may affect the strength of structures under static or impact load, made from materials which, for some reason or another, are in a brittle state.

(3) Residual stresses scarcely affect the strength of members subjected to cyclic loads where the metal is in a ductile state and where there are no structural or technological stress raisers in the structure. The effect of the residual stresses becomes greater with the increase in the brittleness of the metal and with the magnitude of stress concentration. The fatigue strength of welded structures may be increased by the use of various technological processes to create favourable localized stresses in them.

(4) It may be assumed that under certain conditions the residual stresses may reduce the local or overall buckling strength of welded members, under compression; however, the research which has been carried out does not provide sufficient data for quantitative assessment of the degree to which the overall buckling strength is reduced. The need to reduce the permissible stresses or to use other means of allowing for the influence of welding stresses can be judged only after further experimental and theoretical research has been carried out.

(5) If the stresses caused by welding and occurring in the most highly stressed zone of a section of a member are entirely compressive or tensile (as may be the case when welding restrained members, where so-called 'reaction' stresses are created), they may either reduce or increase the strength of the member, according to whether the stresses due to the external load are of the same sign as the welding stresses, or the restrained members.

(6) Welded structures may be heat treated for various purposes to improve the structure and plastic properties of the weld and heat-affected zone, to achieve dimensional stability, for stress relief, and so on. Heat treatment, in order to remove residual stresses, may be applied in structures made of mild or low-alloy steels in the following cases:

(*a*) Firstly, where it has been established that these stresses have an unfavourable effect on the strength of welded structures (in particular where the stress concentration is high, or in cases where corrosive media cause cracking, etc.)

(*b*) Secondly, to achieve dimensional stability during machining and use of welded structures.

* The term residual stress in this note is used to denote the stresses, due to welding, arising in the weld and its immediate vicinity and does not include stresses due to end restraint designated as 'reaction' or 'locked-up' stresses which arise also in parts of the structure remote from welds.

Doc. IIS/IIW-32-59 (ex doc. X-241-59) of the International Institute of Welding. It represents the views of Commission X —"Residual Stresses and Stress Relieving", as an international body of experts, on the effect of residual stresses on the strength of welded constructions, but it does not commit the International Institute of Welding as a whole. The document was appended to the Annual Report of Commission X (Opatija Assembly 1959).

Welding
RESEARCH

B.W.R.A. REPORT

Positional Welding of Steel with the CO_2 Process

By A. A. Smith, B.SC., A.I.M.

The problems involved in making positional welds in steel by the gas-shielded metal-arc process are considered. The CO_2-shielded short-circuiting arc has been found to give a sufficiently small and rapidly-freezing weld pool to permit vertical and overhead welding. Suitable welding techniques and desirable power source characteristics are described.

Introduction

THE gas-shielded metal-arc process using a bare-wire consumable electrode is now widely used in Britain for the welding of aluminium, but finds limited application for steel. This is largely because the established processes, such as gas welding or the covered electrode, continue to give reliable results with steel, and are not subject to the problem of removal of corrosive flux which has displaced these processes for welding aluminium. Moreover, it has not been possible to weld steel with the gas-shielded metal-arc process in the vertical and overhead positions, because of the high minimum currents required to provide an acceptable transfer of metal across the arc. The addition of small quantities of oxygen to the argon shielding gas has been effective in improving the metal transfer characteristics, but the minimum current that enables a 'spray type' transfer to be achieved still results in a large molten pool which is too fluid to remain in the overhead or vertical position.

The use of CO_2 as a cheaper shielding gas than argon–oxygen mixtures has resulted in some applications of the process in industry, but these have largely been confined to mechanized operations. When CO_2 is used as the shielding gas, the metal transfer characteristics are even less acceptable than with an argon–oxygen mixture, and the welds can have a poor appearance with an excessive loss of filler wire by spatter. The minimum current that gives a smooth metal transfer, free from spatter, is high (in the region of 400 amp with $\frac{1}{16}$ in. dia. wire) and at this current positional welding is impossible.

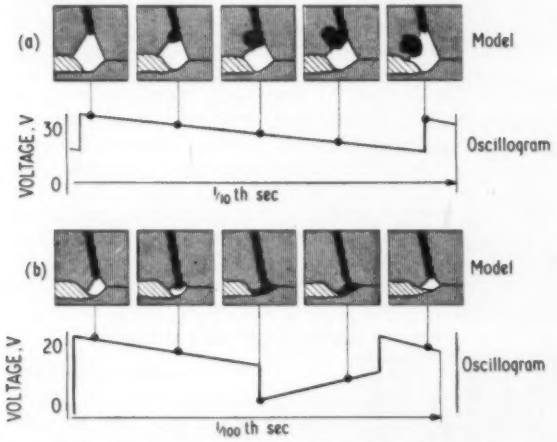
In the present work a study has been made of the means by which the bare-wire CO_2 process can be successfully operated at low currents, primarily for the mechanized welding of thin gauge steel sheet, but the techniques have been applied to overcome the problems involved in all-positional welding with this process.

Metal Transfer in CO_2

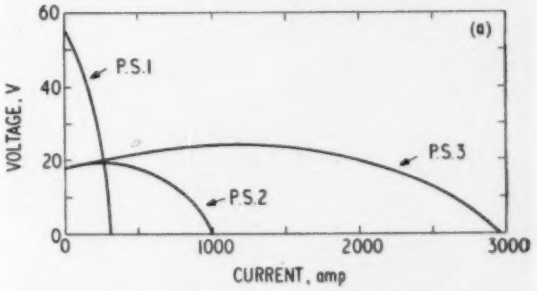
The metal transfer characteristics of the aluminium arc in argon have been studied in detail,[1] and it has been shown that the frequency of transfer of droplets across the arc is high and increases as the current increases, traversing the gap at an acceleration of some 10 *g*. In this 'spray transfer' range the particles are smaller than the diameter of the welding wire, but if the current is reduced below a certain value (about 140 amp for $\frac{1}{16}$ in. wire) the size of the transferring drop becomes abnormally large, and at a very low

Report A.1/9/59 of the British Welding Research Association, circulated to members in June 1959.
Mr. Smith is a Principal Scientific Officer with the Association.

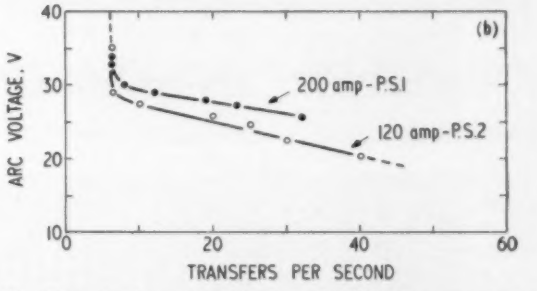
current it can attain a size some four times the diameter of the electrode wire. This range, where the metal is transferred as large pendant globules, has been termed the 'sub-threshold' range, and is not used for welding because unlike in the 'spray type' transfer the metal is falling under gravity and the process is of no use for positional welding. In the CO_2 process for steel this sub-threshold type of metal transfer has been reported by some investigators[2] to exist up to relatively high currents without the abrupt change in transfer frequency that marks the appearance of the spray transfer range for aluminium. High-speed photography has shown[3,4] that the pendant globule in CO_2 shielding is distorted during its growth and receives some undefined arc or gas pressure from beneath, so that axial metal transfer into the weld pool is not always achieved, and is one of the causes of spatter. At a high arc voltage, where there is sufficient physical arc length for the particle to be detached in the arc column, transfer occurs as 'free flight', but if the wire-tip/work gap is decreased by using lower arc voltages, the transferring drop can short-circuit the gap. The droplet will then be detached prematurely before it has grown to the equilibrium size it would have achieved under free flight conditions. A short-circuiting arc therefore overcomes the characteristic disadvantages inherent in the CO_2 arc—a large drop size and non-axial gravitational transfer. Spatter is therefore minimized, and since a high current is unnecessary to achieve a fine drop transfer, positional welding can be performed. By short-circuiting the metal into the weld pool the characteristic pendant



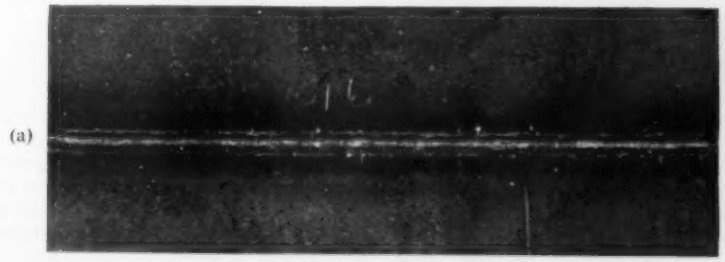
1—*Schematic form of metal transfer in CO_2: (a) Free flight transfer at 30 V; (b) short-circuit transfer at 20 V*

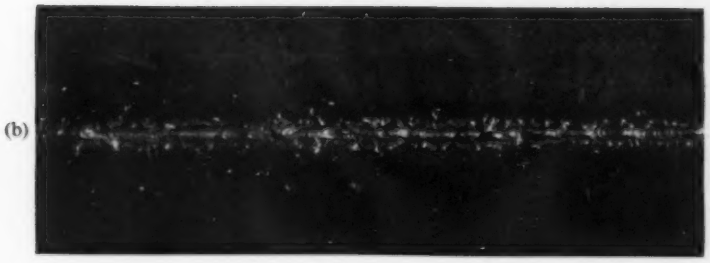


2a—*Output characteristics of typical welding power sources*

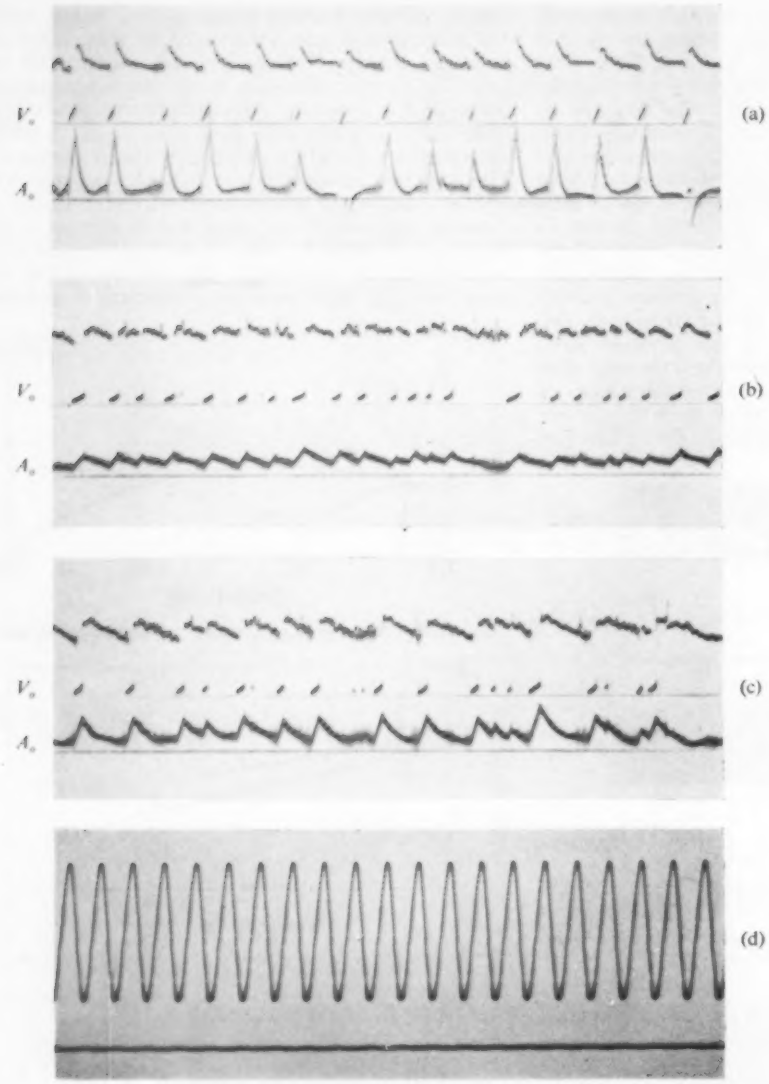


2b—*Short-circuit transfer behaviour with different power sources*





3—*Appearance of welds using different power sources for short-circuiting arcs: (a) PS.2, 120 amp, 20V; (b) PS.3, 120 amp, 20 V*



4—Oscillograms of arc voltage and current, showing short-circuiting behaviour: (a) PS.3, no inductance added, high current peaks, spatter; (b) PS.2, inductance in series, current peaks reduced, no spatter; (c) PS.2, no inductance added, current peaks not high enough to cause spatter; (d) 50 c/sec timing trace

drop behaviour in CO_2 is avoided and the transferring drop is placed exactly where it is wanted in the weld pool. The probable mechanism of metal particle* transfer by the free flight and short-circuit types is shown diagrammatically in Fig. 1, together with typical schematic voltage records drawn from oscillograms of arc voltage.

Power Source

To achieve the short-circuit metal transfer described, a power source having special output characteristics is required. A source with a drooping volt/amp characteristic is not suitable, since the current available at short circuit is insufficient to prevent 'stubbing' or extinction of the arc when the wire touches the work. The volt/amp output curve of a typical drooping characteristic power source is represented by curve PS.1 in Fig. 2, and curves PS.2 and PS.3 represent two constant-potential power sources. With the drooping power source, using $\frac{3}{64}$ in. steel welding wire, 200 amp is the lowest current that can be operated satisfactorily, and 'stubbing' occurs when the voltage is reduced to 25 V. Figure 2*b* shows that in reducing the voltage from 34 to 25 V some increase in the transfer frequency has been achieved.

If now a constant-potential generator, having a virtually flat volt/amp output characteristic is used (PS.2), not only is it possible to weld with the same wire diameter at a lower current, but also to use a lower arc voltage, giving a more frequent transfer rate

* High-speed cine photographs have recently confirmed this model.

and less spatter. The difference between these two power sources is that during a short circuit of the arc by the pendant drop, the rate of rise of current with the drooping-characteristic power source is insufficient to reignite the arc, which is then extinguished and stubbing occurs. With the constant-potential power source, the available current at short circuit is high and is quickly achieved, so that the arc is rapidly re-established. If a power source with a volt/amp characteristic as represented by the curve PS.3 in Fig. 2*a* is used, where the short-circuit current is even higher, the rate of rise of current at short circuit is very rapid and the 'short' is cleared explosively, so that spatter occurs. Figure 3 shows the effect of the power-source characteristic on the appearance of welds made with the same welding conditions.

The rate of rise of current at short circuit can also be limited by including an inductive reactance in the circuit,[5] when the spatter is again reduced. Oscillograms illustrating this effect are shown in Fig. 4*a*, where the power source with the large short-circuit current (PS.3) has been used to give rapid short-circuiting conditions but resulting in high current peaks and spatter. The record in Fig. 4*b* shows the same short-circuiting arc, but the value of the current peak has been reduced by the insertion of the inductance. The appearance of the welds now corresponds with Fig. 3*a*, since the performance of the power source PS.3 with the large short-circuit current plus inductance is similar to the power source with the lower short-circuit current. The current peaks coinciding with the short circuits for this power source are shown in Fig. 4*c*.

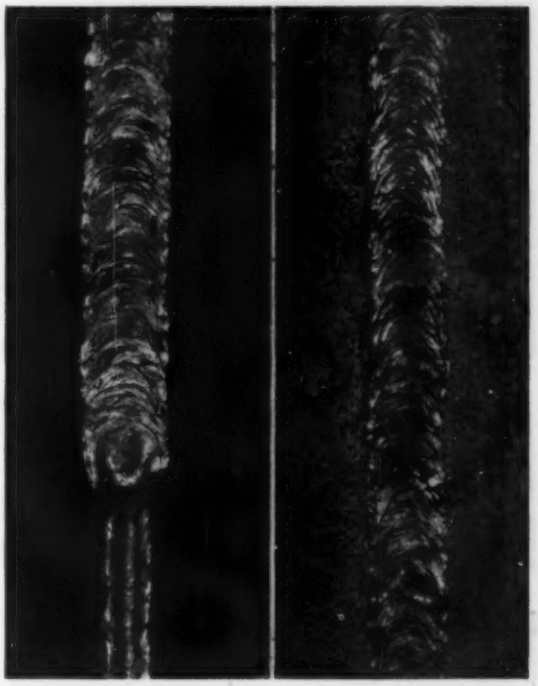
Welding with Short-Circuit Transfer

Mechanized welding

The observations on CO_2 welding arcs at low voltages were first applied to the mechanized butt welding of thin gauge steel. The CO_2 process would not normally have been regarded as suitable for this application because of the undesirable metal transfer behaviour associated with the low currents required. Using short-circuiting arc conditions, and a constant-potential motor generator having a volt/amp output characteristic similar to PS.2 in Fig. 2, excellent butt joints were made in $\frac{1}{16}$ in. sheet. At welding speeds of 25 in./min the optimum welding conditions were 120 amp and 20 V, using $\frac{3}{64}$ in. dia. wire. With $\frac{1}{32}$ in. wire and about 18 V it was possible to make welds in thinner material at currents as low as 40 amp. In all these test welds spatter was negligible, and the welds exhibited a good shape and appearance.

Manual positional welding

The transfer of metal to the weld pool by the short-circuiting mechanism used for mechanized welding of sheet was then applied to manual positional welding since, with the low currents and voltages being used, a small molten pool is quickly chilled and metal is directly transferred from the electrode wire to the weld without spatter. Wire of $\frac{3}{64}$ in. dia. was chosen, and the welding conditions used for mechanized welding in the downhand position were employed for vertical and overhead welding; *i.e.*, current 110 amp, arc voltage 20 V, MS65 wire $\frac{3}{64}$ in. dia., wire feed speed



(a) (b)

5—*Appearance of vertical welds made with CO_2 process:* (a) *Fillet joint in $\frac{1}{4}$ in. plate;* (b) *butt joint in $\frac{3}{8}$ in. plate*

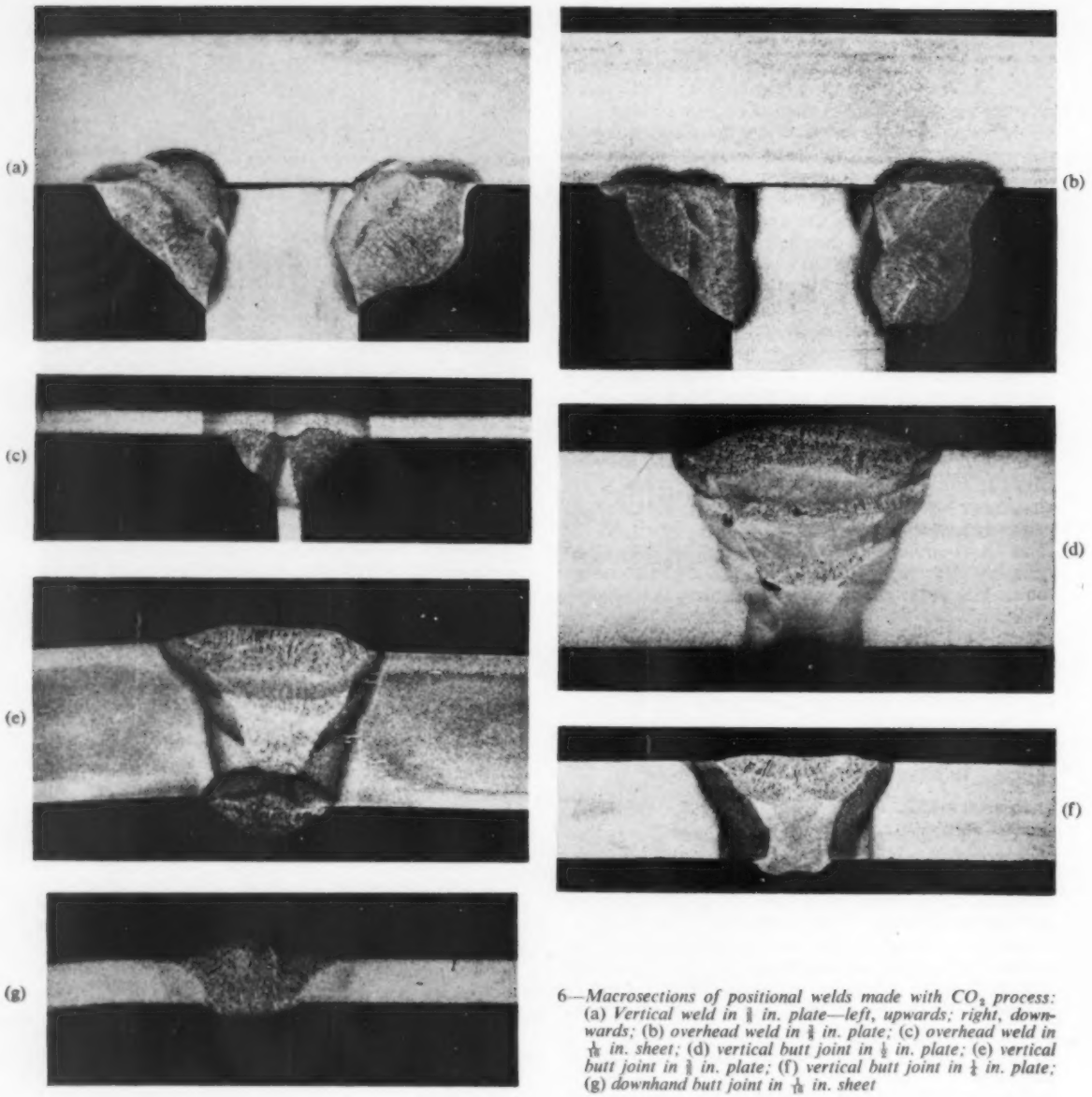
100 in./min, CO_2 gas flow 30 cu.ft/hr, power source constant-potential motor generator.

Vertical and overhead fillet joints were made with steel ranging in thickness from $\frac{1}{2}$ in. to $\frac{1}{16}$ in., using the same current and voltage. The excellent appearance of typical welds is shown in Fig. 5. They were made using a vertical-down technique. The root fusion was obtained in the thicker material ($\frac{3}{8}$, $\frac{1}{2}$ in.) by first depositing a small pass vertically upwards, using a small circular weave, and then making the smooth concave finishing pass vertically downwards, using a wider weave. The use of a downward welding direction results in a smoother fillet shape.

With the thinner materials, $\frac{1}{8}$ and $\frac{1}{16}$ in. it was possible to make a single pass into the fillet, using a vertically downwards direction, without weaving. The absence of distortion was particularly noticeable.

Overhead fillet welding could be performed in all the thicknesses used, and a multi-pass stringer-run technique was satisfactory for the thicker material. The appearance of macrosections of typical overhead and vertical welds is shown in Fig. 6.

Vertical butt joints were made in $\frac{1}{2}$, $\frac{3}{8}$, and $\frac{1}{4}$ in. plate using a single 60° V-edge preparation, with little or no root face. A small root gap ensured good penetration to the reverse side on the first pass, and welding in the vertical downwards direction gave good control of bead shape. With $\frac{1}{2}$ in. plate, four passes were necessary using the vertical-down technique, but if the first two passes were made vertically up, only three passes were necessary, using a vertically down pass to give a good appearance. Vertical welding was carried out at about 9 in./min.



6—*Macrosections of positional welds made with CO_2 process:* (a) *Vertical weld in $\frac{3}{4}$ in. plate—left, upwards; right, downwards;* (b) *overhead weld in $\frac{3}{4}$ in. plate;* (c) *overhead weld in $\frac{1}{16}$ in. sheet;* (d) *vertical butt joint in $\frac{1}{2}$ in. plate;* (e) *vertical butt joint in $\frac{3}{4}$ in. plate;* (f) *vertical butt joint in $\frac{1}{2}$ in. plate;* (g) *downhand butt joint in $\frac{1}{16}$ in. sheet*

For the thicker material, $\frac{1}{2}$ in. plate, attempts were made to raise the welding speed by increasing the current to about 200 amp. This was the maximum current that could be used in vertical welding, and 150 amp was the highest current that gave adequate control over the weld pool on $\frac{1}{2}$ in. plate, where the thermal capacity of the plate could exert some chilling effect on the weld pool.

With the multi-pass welds a light scratch brushing was sufficient to remove the localized glassy surface slag, and the more tenacious areas were generally removed by subsequent welding. It was possible, however, especially with the thicker plate, to entrap some of the slag to give rise to localized inclusions (*see* Fig. 6*d*).

The amount of electrode wire projecting from the contact tube was maintained as small as possible to avoid difficulties due to resistance heating of the wire on short circuit with the weld pool, and for practical purposes an extension of about $\frac{1}{2}$ in. was satisfactory. To improve the resistance of the nozzle to spatter pick-up, a wash coating of lime was applied before welding, although at the low current conditions being used, spatter encrustation presented little problem.

Equipment

The welding equipment used for this work was a standard British self-adjusting-arc wire-drive unit and

a water-cooled gun, but with the addition of a suitably inductive constant-potential motor generator. The $\frac{3}{64}$ in. dia. wire was pushed normally through the standard length of flexible hose and no problems arose with the feeding arrangements.

Conclusions

The development of the short-circuit transfer technique enables CO_2 welding to be performed in the vertical and overhead positions. The range of usefulness of the process has therefore been greatly extended and should lead to its use in the fields of application at present occupied by the covered electrode and gas-welding processes. The CO_2 process can give a very high welding speed in position, since no time is needed for deslagging and electrode changeover, and the localized heating of the process makes it especially useful for welding thinner materials. A ready application of the process would lie in the all-position welding required by the automobile industry, where gas and metal-arc electrodes are at present extensively used. The advantages of the CO_2 process as a semi-automatic equipment can also be exploited, since the process is very easily mechanized, the component to be welded being rotated or traversed beneath a welding torch held in a fixing clamp.

Because of the oxidizing nature of the shielding gas, the hydrogen content of the weld metal is low, and for this reason the process can be developed for the welding of alloy steels. The circuit characteristic can be modified to enable short-circuit transfer to be achieved with $\frac{1}{16}$ in. dia. wire, when the CO_2 process can be used with one wire size for welding in all positions, and for light gauge steel at low currents and high speed gravity positions using higher currents, where metal deposition can be increased without consideration for the support of the weld pool.

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B.W.R.A. REPORT

CO_2 Welding of Sheet Materials

By A. G. Brain, B.A., A.I.M.,
and A. A. Smith, B.SC., A.I.M.

The difficulties involved in applying the CO_2-shielded metal-arc process to the welding of steel sheet have been defined. A study of the CO_2 arc characteristics has enabled satisfactory welding conditions to be established, and fully automatic butt welds have been made in 16 s.w.g. sheet in a range of aircraft materials.

PREVIOUS experience[1,2] has indicated that metal transfer across the CO_2-shielded steel arc occurs in a coarsely globular form, unlike the fine, regular, spray-type transfer which defines the useful welding current range with other gas–metal combinations, such as aluminium in argon. In this last case, moreover, the size of transferring metal droplets has been shown to increase with decrease in the welding current.[3] At the necessarily low currents required for the welding of thin gauge steel it was to be expected that infrequent transfer of coarse droplets would occur across the CO_2-shielded arc, resulting in an irregular bead and non-uniform penetration. The weld appearance would also be marred by the occurrence of spatter, which was another observed feature of the process.

The present investigation included, therefore, a study of the factors affecting metal transfer in CO_2, since it was thought that the characteristics of weld beads could be correlated with metal droplet size and transfer frequency.

It was found that at low currents the optimum metal transfer and weld bead quality were obtained with a low-voltage short-circuiting arc. This condition was used for the CO_2-shielded welding of low-alloy steels, austenitic stainless steel, and two of the Nimonic alloys.

Factors Affecting Metal Transfer

Current and wire diameter at constant arc voltage

An arc voltage of 30 V was chosen for the initial experiments, since this was known to provide an arc

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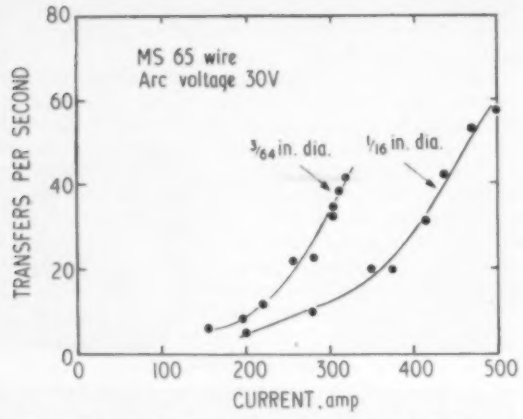
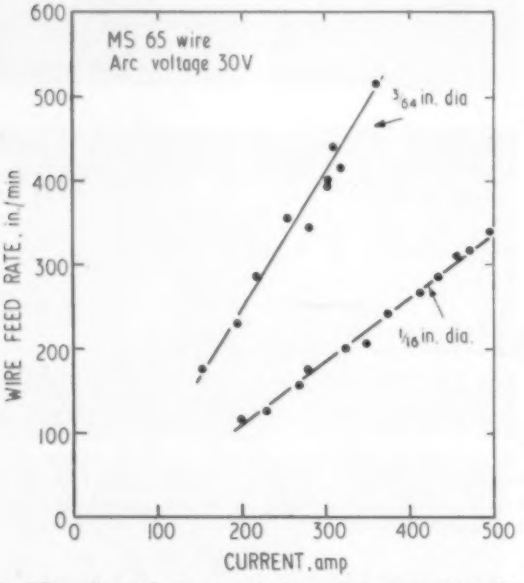
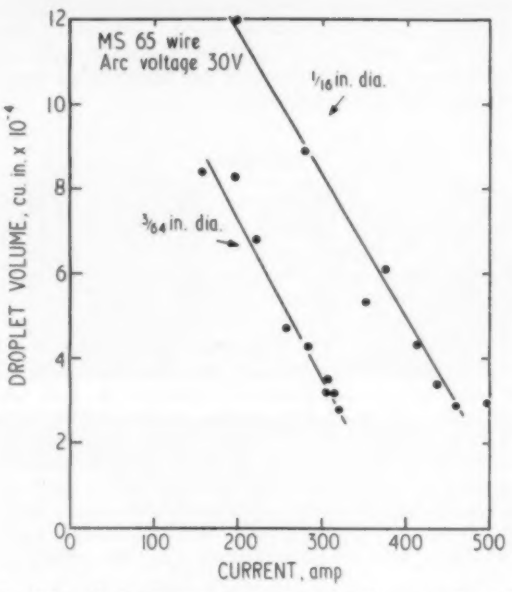
Report A1/2/59 of the British Welding Research Association circulated to members in August 1959.
Mr. Brain is a Research Officer, and Mr. Smith a Principal Scientific Officer with the Association.



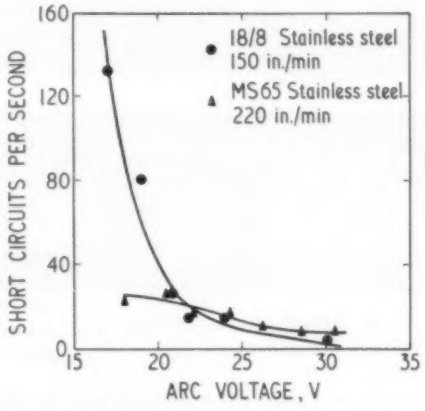
1—*Effect of wire diameter on droplet transfer rate in CO_2*



2—*Effect of wire diameter on the burn-off characteristic in CO_2*



3—*Effect of wire diameter on droplet-volume/current relationship in CO_2*



4—*Effect of arc voltage on short-circuit frequency at constant wire feed rate ($\frac{3}{64}$ in. dia. wire)*

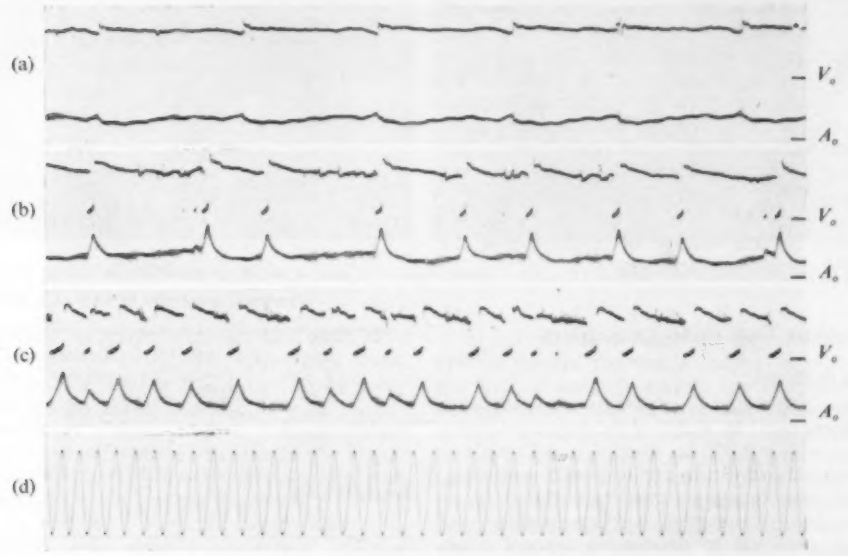
of such a length that visible transfer of coarse metal droplets took place at low current. Bead-on-plate tests were made using controlled-arc welding equipment in conjunction with a 600-amp transformer-rectifier power source.

A double-beam cathode-ray oscilloscope and high-speed drum camera were used to record in detail the fluctuations in arc voltage and current over short periods. Individual transfers of drops across the arc were indicated by flicks or discontinuities on the wave forms. The frequency of transfer could be determined by reference to a 50-cycle timing trace.

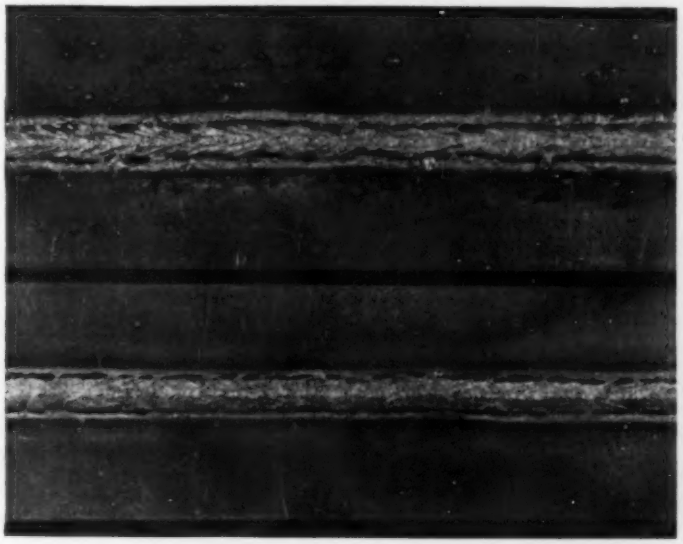
The results of tests using MS.65 wire of two diameters are shown in Fig. 1, where droplet transfer frequency is related to welding current. Although the points are joined by a continuous curve, each curve consists of two regions. The lower, gently-sloping region is characterized by relatively infrequent metal transfer, while the higher-current region shows a greater increase in droplet transfer frequency with current. Most of the early published work on the CO_2 process referred to the lower current region, mainly with $\frac{1}{16}$ in. dia. wire, and the reported incidence of spatter was certainly confirmed in the present work; but in the higher current region the droplets of molten metal were apparently transferred into the weld pool, and the welds were of good appearance. The corresponding burn-off characteristic curves are shown in Fig. 2, and the droplet volume relationships are given in Fig. 3. Because of the relatively smaller droplet size with the $\frac{3}{64}$ in. dia. wire further work was concentrated on this gauge.

Arc voltage

A further series of tests was carried out with $\frac{3}{64}$ in. dia. wire in which the wire feed speed was maintained



5—*Oscillograms of CO_2-shielded welds showing the effect of arc voltage on droplet transfer rate. 200-amp; constant-potential motor generator; $\frac{3}{64}$ in. dia. wire:* (a) *31 V;* (b) *25 V;* (c) *20 V;* (d) *50 c/sec timing trace*



6—*Photographs of CO_2 welds in $\frac{1}{16}$ in. Fortiweld sheet, showing effect of arc voltage on occurrence of spatter:* (a) *25 V, 120 amp* (b) *20 V, 120 amp*

constant but the arc voltage progressively reduced from 30 V. With the controlled-arc system it was found impossible to maintain a continuous arc below 25 V, so a 350-amp constant-potential motor generator was used for the complete series, in conjunction with a self-adjusting-arc unit.

The relationship between voltage and transfer frequency for mild and stainless steel wires is shown in Fig. 4. It is apparent that droplet transfer frequency increases appreciably as the voltage is reduced, the effect being most striking for stainless steel. With this material the effect of arc voltage on bead appearance was determined by laying weld beads on $\frac{1}{8}$ in. thick stainless steel plate. The wire used was $\frac{3}{64}$ in. dia. En 58F, and the wire feed speed was preset at 150 in./min. Smooth beads with good profile were obtained at arc voltages below 20 V, but above this value the appearance deteriorated, with an increasing tendency towards spatter and poorly shaped ripples. In the favourable voltage region the arc ran smoothly, with a small visible length and no discernible transferring particles. At a little above 20 V the arc condition varied between that described and a longer arc, which could be observed impingeing on a molten droplet at the electrode tip. At higher arc voltages the latter type of arc condition was found alone. Examination of the oscillograms showed that short circuiting was occurring at as high as 28 V, and that the frequency of short circuiting increased slowly as the arc voltage was lowered to 20 V, and then much more rapidly as the voltage was lowered still further into the most favourable welding region.

With the MS.65 wire, for which a feed speed of 220 in./min was used, the weld appearance was similarly

dependent on arc voltage, although the curve did not show such a sharp increase in gradient as with stainless steel. The typical oscillograms in Fig. 5 show the effect of short circuiting on the current and voltage wave forms. The improvement in surface appearance resulting from decreasing the arc voltage from 25 to 20 V is shown in Fig. 6. High-speed ciné photography has shown that at the lower arc voltages the growing droplet is prematurely detached upon short circuiting with the weld pool. For the range of welding conditions examined, an arc voltage of 18–20 V gave the optimum short circuiting conditions.

Welding Tests on 16 s.w.g. Sheet

General welding conditions

Square close-butt welds 12 in. long were made over a copper backing bar 1 in. wide × ½ in. deep containing a groove ¼ in. wide × 0·020 in. deep. Close fit-up was ensured between the abutting surfaces before welding, and the sheets were firmly clamped to within 1 in. of the weld. For ferrous materials, surface treatment of the sheet was confined to degreasing, except when heavy rust or scale was present. No attempt was made to simulate production welding conditions or to anticipate the practical or metallurgical difficulties that could be encountered in welding actual structures.

Welding was carried out in the downhand position. with an 80° angle maintained between the torch and the deposited bead. The CO_2 gas was supplied from a 28-lb cylinder, and the flow rate was maintained at 30 cu.ft/hr through a ½ in. nozzle. The 350-amp constant-potential generator was used throughout the tests to be described. Description will be confined mainly to welding carried out at travel speeds of 25 in./min and above, since this is the welding speed range normally sought in a fully automatic process. Wire of $\frac{3}{64}$ in. dia. was employed most satisfactorily at the currents involved in welding in this range, with a distance of ½ in. between the guide tube tip and the plate.

The materials welded were representative of alloys used widely in the aircraft industry because of their special strength, corrosion- or heat-resisting properties.

Results on different materials

SAE 4130

SAE 4130 alloy is a high-strength, heat-treatable, low-alloy steel. It is generally welded by the automatic tungsten-arc process in an atmosphere of argon. filler metal being added of a suitable composition to give a joint strength of 75–80 tons/sq.in. U.T.S. in the heat-treated condition. Such a wire is Airco Armour wire, A632, and typical compositions of sheet and wire are as follows:

	Analysis, %					
	C	*Si*	*Mn*	*Ni*	*Cr*	*Mo*
SAE 4130 Sheet	0·33	0·31	0·48	0·20	1·0	0·18
A 632 Wire	0·07	0·35	1·22	1·20	0·14	0·42

The conditions for welding 0·075 in. thick sheet with $\frac{3}{64}$ in. dia. A632 wire and CO_2 shielding are shown in Table I. For purposes of comparison, welds were also made in argon–5% oxygen under spray-transfer conditions.

Table I

Conditions for welding SAE 4130 sheet using A 632 wire

Shielding Gas	*Welding Speed, in./min*	*Current, amp*	*Arc Voltage, V*
CO_2	25	160	20
	40	190	20
Argon–5% O_2	25	190	25
	40	240	24

Table II

Hardness properties of SAE 4130 welds

		Hardness, D.P.N. (10 kg)			
		As-welded		*After heat-treatment*	
Shielding Gas	*Welding Speed, in./min*	*Weld*	*H.A.Z. (max.)*	*Weld*	*Sheet*
CO_2	25	364	508	360	370
	40	360	473	358	394
Argon–5% O_2	25	352	536	358	382
	40	348	493	369	377

Weld Properties—Each test plate was radiographed and all displayed almost complete freedom from porosity but a general tendency towards undercutting regardless of welding speed or shielding gas. No cracks were observed.

Hardness determinations were made in the weld, heat-affected, and unaffected regions in the as-welded state, using transverse microsections. This procedure was repeated on specimens which had been given the heat-treatment cycle for SAE 4130 alloy, namely oil quenching from 900°C. followed by tempering at 450°C. The sheets before welding possessed a hardness of 190 D.P.N. The results are given in Table II.

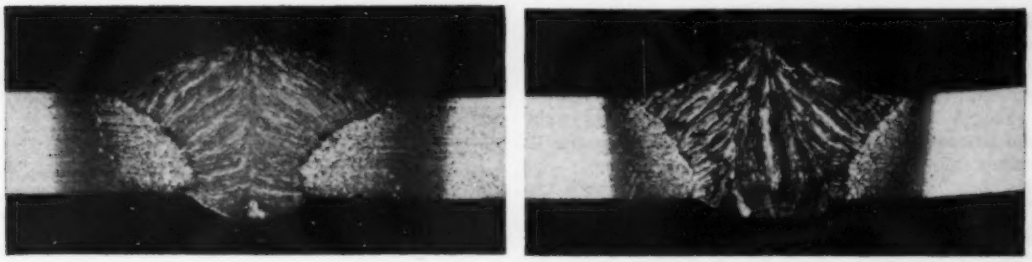
The sheets showed considerable hardening in the heat-affected zones in the as-welded condition. The effect of the heat-treatment was to lower the weld hardness slightly and to raise the sheet hardness to a level a little above that of the weld.

Three tensile test pieces ½ in. wide and with 2½ in. parallel length were machined from each weld and oil quenched from 900° and tempered at 450°C. The welds were dressed flush with the sheet, which was also machined to remove all undercutting. With one

Table III

Tensile properties of SAE 4130 welds
(Fracture in weld)

Shielding Gas	*Welding Speed, in./min*	*U.T.S., tons/sq.in.*	*Elong. on 2 in., %*
CO_2	25	75·5	2
		74	2
		75	3
	40	78	4
		78·5	5
		78	4
Argon–5% O_2	25	77	4
		77·5	4
		77·5	4
	40	77·5	4
		77·5	3
		76·0	3



7—*Macrosections of butt welds in 16 s.w.g. SAE 4130:* (a) *Welding speed 25 in./min;* (b) *welding speed 40 in./min*

exception fracture occurred through the weld. The results are shown in Table III. Unwelded sheet, similarly heat-treated, had a U.T.S. of 75–80 tons/sq.in. with elongation figures from 7% to 9%.

It should be noted that the highest weld properties obtained in CO_2 were from welds made at the higher speed, and that these results compared favourably with those from the argon–5% oxygen mixture.

A transverse specimen was taken from each CO_2 weld for macro- and micro-examination. Typical macrosections are shown in Fig. 7. The slight 'peakiness' of the bead tends to be a feature of CO_2 welds in mild and low-alloy steels, particularly at high welding speeds. Micro-examination showed the weld structures to be martensitic, while the heat-affected zones showed martensite immediately adjacent to the welds, with a gradation of structures to the unaffected metal. After heat-treatment both regions were sorbitic. No cracks, inclusions, or porosity were observed.

Chemical Analysis—The element transfer efficiencies in CO_2 and argon–5% O_2 gases were determined by preparing multi-pass pads of weld metal, thus minimizing dilution by the base-plate material. Both wire and pad samples were submitted to chemical analysis. The current and voltage used corresponded with those previously employed in welding at 25 in./min, and the results were as follows:

	Analysis, %					
Sample	*C*	*Si*	*Mn*	*Ni*	*Cr*	*Mo*
$\frac{3}{64}$ in. A632 wire	0·09	0·32	1·22	1·18	0·14	0·38
CO_2 Pad (160 amp, 20 V)	0·08	0·06	0·48	1·18	0·09	0·39
Argon–5% O_2 Pad (190 amp, 25 V)	0·05	0·07	0·45	1·19	0·09	0·39

Thus, at the welding conditions found most suitable for welding thin gauge steel in CO_2 shielding, appreciable element loss is confined to the deoxidizers silicon and manganese; the hardening elements C, Ni, Cr, and Mo are transferred efficiently across the arc.

Fortiweld

Fortiweld is a low-alloy, molybdenum-boron, bainitic steel, characterized by a high proof-stress/U.T.S. ratio, and requiring no hardening treatment after welding. In the present investigation 16 s.w.g. sheet was welded with $\frac{3}{64}$ in. dia. Fortiweld wire of virtually the same composition. Great importance attaches to the degree to which the small proportion of boron is transferred across the arc, since on this depends the bainitic hardenability.

The welding conditions are shown in Table IV.

Weld Properties—Each test plate was radiographed, and in general the welds were of a high quality. At the higher welding speeds the incidence of undercutting beside the weld tended to increase. In two specific instances an isolated transverse crack was found in the weld, passing into the parent sheet on either side, while in a third, three such cracks were found within one inch of weld. Isolated regions of porosity were also revealed. This porosity assumed a chevron pattern with the direction of the chevrons parallel with the crystal growth, suggesting a 'rimming' type of gas evolution. No direct correlation existed between the incidence of these isolated cracks or porosity and the welding conditions. Since the defects were localized and not reproducible, it is difficult to offer a satisfactory explanation. It is possible, however, for boron segregation to produce a susceptibility to hot cracking in this alloy, and the content of deoxidizing elements is below that normally allowed for welding in CO_2.

Table IV

Conditions for welding Fortiweld sheet using Fortiweld wire

Shielding Gas	*Current, amp*	*Arc Voltage, V*	*Welding Speed, in./min*
CO_2	150	20	25
	185	20	40
Argon–5% O_2	150	22	25
	150	25	25

Table V

Tensile properties of Fortiweld welds
(Fracture in parent sheet)

Shielding Gas	*Welding Speed, in./min*	*U.T.S., tons/sq.in.*	*Elong. on 2 in., %*
CO_2	25	44·6	12
		45·0	12
		44·8	11
	40	42·2	11
		43·2	11
		42·2	12
Argon–5% O_2	25	45·5	12
		45·0	10
		45·9	10
	25 (at 25V)	45·7	9
		46·0	11
		46·5	9
Unwelded Parent Sheet		46·1	14
		46·8	13

Transverse tensile test pieces were machined from the butt joints and tested with the reinforcement removed. In every case fracture occurred in the parent sheet remote from the weld, so that the results shown in Table V do not give a direct evaluation of weld metal properties, but indicate that the weld metal is stronger than the parent sheet.

The bead shapes were similar to those of the SAE 4130 welds. Hardness surveys were carried out on the CO_2 weld cross-sections, and a mean weld hardness of 348 D.P.N. was found for a welding speed of 25 in./min, rising to 367 D.P.N. at 40 in./min. Corresponding peak hardnesses for the heat-affected zones were 409 and 425 D.P.N. respectively. The unaffected sheet possessed a hardness of 240 D.P.N.

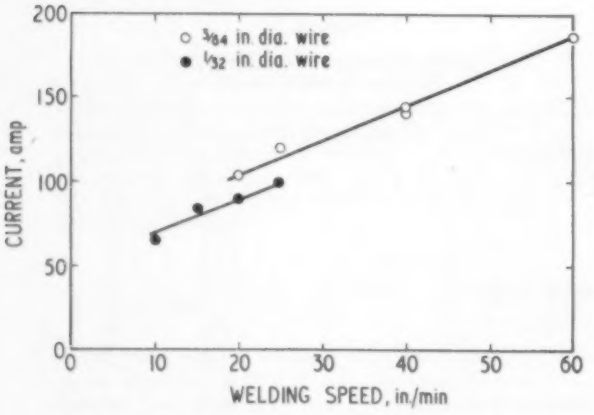
To investigate the effect of isolated regions of undercutting on the static mechanical properties, a further series of tensile tests was made on specimens in which the reinforcement and undercutting had not been removed. Other undressed specimens exhibiting undercutting were stress-relieved at 650°C. for 30 min. In all tests, fracture occurred in the parent sheet remote from the weld, despite the presence of undercutting.

The results, given in Table VI, are chiefly of interest in showing the softening effect of the stress-relieving treatment. Direct comparison with previous results is not advisable, since different batches of material were involved.

Table VI

Tensile properties of CO_2-shielded welds in Fortiweld: reinforcement and undercutting not removed
(Fracture in parent sheet)

Condition	U.T.S., tons/sq.in.	Elong. on 2 in., %	Hardness, D.P.N. (10 kg) H.A.Z. (max.) Weld	Sheet
As-welded	45·0	10		
	45·5	10	304	245
	45·5	11		
As-welded + 30 min at 650°C	42·0	12		
	42·5	12	257	230
	42·5	14		



8—*Relationship between current and welding speed for 16 s.w.g. stainless-steel sheet (18–19 V arc voltage)*

Chemical Analysis—The element transfer efficiencies in CO_2 and argon–5% O_2 were determined by preparing multi-pass pads of weld metal as before. The results together with the sheet analysis, were as follows:

Sample	Analysis, % C	Si	Mn	Mo	B
3/64 in. Fortiweld wire	0·12	0·20	0·61	0·40	0·002
CO_2 Pad (150 amp, 20 V)	0·08	0·09	0·47	0·42	0·003
Argon–5% O_2 Pad (150 amp, 25 V)	0·07	0·06	0·35	0·44	0·002
16 s.w.g. Fortiweld sheet	0·13	0·17	0·72	0·45	0·003

The analytical method used for the boron determinations does not give high accuracy but the inference from these results is that neglible loss of boron occurs. It is significant that the essential molybdenum-boron content of the wire is transferred with maximum efficiency, and that carbon loss is not excessive in either CO_2 or argon–5% O_2.

Austenitic Stainless Steel

The sheet, supplied in the hot-rolled and pickled condition, conformed to specification En58B of BS.1449, and the electrode wire to En58F. Actual compositions were as follows:

	Analysis, % C	Si	Mn	Ni	Cr	Ti	Nb	Mo
Wire	0·10	0·68	0·66	8·6	19·1	0·01	0·94	0·05
Plate	0·07	0·56	0·97	9·0	17·8	0·41	0·04	0·13

For this material a description will be given of welding over a greater range of speed, since the experience is likely to be representative of that obtained with other materials, particularly in respect of the current range within which any wire diameter may be used.

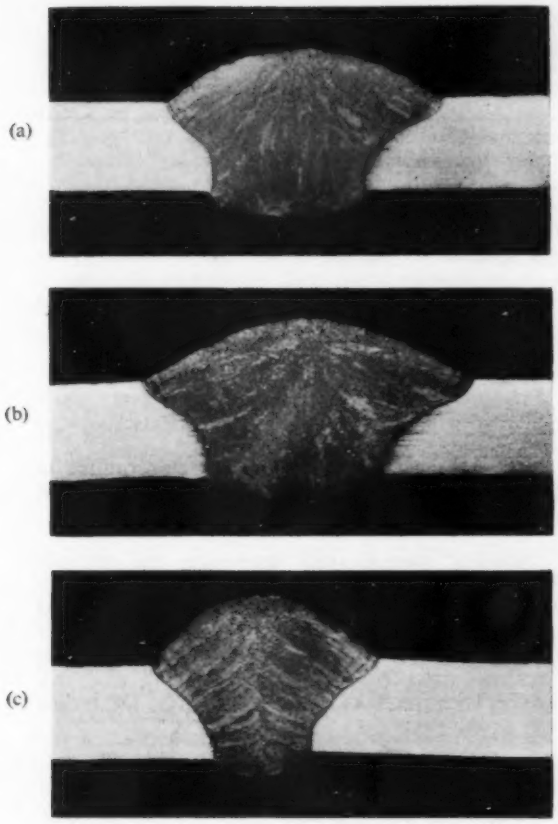
Using 3/64 in. dia. wire, a number of square close-butt welds were made at travel speeds between 15 and 60 in./min, with an arc voltage of 18–19 V and appropriate current to produce optimum penetration. At a travel speed of 15 in./min, the wire feed motor was required to work at its lowest setting, and the weld showed irregular penetration and a poor bead shape. Satisfactory welding was obtained at 20 in./min travel speed.

The use of 1/32 in. dia. wire enabled welds to be made at a speed as low as 10 in./min. The travel speed range over which this size wire could be used was found to be limited by the inability of the arc to become properly established at wire feed rates much above 210 in./min, and satisfactory welding could not be completely assured at travel speeds above 25 in./min.

The welding conditions and range of travel speed for the two wires are shown graphically in Fig. 8.

Weld Properties—All welds were characterized by a smooth non-rippled surface with little tendency towards the formation of a 'peak'. A grey oxide film covered the beads, except at those places (usually at or near the top of the weld bead) where slag was situated or where it had flaked off leaving a bright surface. Very little spatter was observed.

The oxide on stainless steel is known to be of a refractory nature, and it was found possible to make some butt joints without any backing bar, the oxide film presumably affording adequate support to the underbead.



9—*Macrosections of butt welds in 16 s.w.g. stainless steel:* (a) *Welding speed 25 in./min;* (b) *welding speed 40 in./min;* (c) *welding speed 60 in./min*

Macrosections of typical weld beads are shown in Fig. 9. The slight degree of asymmetry observable in some of these arose from bending of the wire as it left the guide tube.

Examination of microsections confirmed the absence of a visible heat-affected zone in the sheet close to the weld, there being no discernible grain growth even in welds made at low speeds. Some ferrite was visible in the weld microstructure; no cracks, inclusions, or porosity were found.

The tensile tests were inconclusive in that the softness of the sheet did not allow fracture to occur though the weld. In all cases the weld withstood a stress of 38 tons/sq.in. without fracturing, this being the tensile strength of the parent sheet.

Hardness testing of transverse sections established that the welds were harder at 190 D.P.N. than the unheated sheet by 20–30. A slight amount of hardening was sometimes detected in the heat-affected zone, but neither this nor the weld hardness could be correlated with welding speed.

Corrosion Resistance and Chemical Composition—To determine the transfer efficiency of all elements in the electrode wire, a multi-run weld-metal pad was made in CO_2, using the $\frac{3}{64}$ in. dia. wire at the conditions previously used for welding at 25 in./min, *i.e.* 18 V arc voltage and about 120 amp. For purposes of comparison a similar pad was made in argon containing 2% oxygen. The composition of the wire and upper runs of the two pads were as follows:

	Analysis, %							
Sample	*C*	*Si*	*Mn*	*Ni*	*Cr*	*Ti*	*Nb*	*Mo*
$\frac{3}{64}$ in. En58F Wire	0·10	0·68	0·66	8·6	19·1	0·01	0·94	0·05
CO_2 Pad	0·17	0·35	0·37	8·6	18·7	0·004	0·52	0·05
Argon–2% O_2 Pad	0·07	0·51	0·52	8·6	19·0	0·007	0·64	0·05

It will be noted that nickel, chromium, and molybdenum transfer across the arc in both gases with almost complete efficiency, but some loss is apparent in the stabilizing elements titanium and niobium, and in silicon. These losses are greater in CO_2 than in argon–2% oxygen, and in addition the CO_2 weld metal has absorbed carbon from the gas. Because of niobium loss and carbon gain this undiluted CO_2 weld metal would be prone to inter-crystalline corrosion, particularly following heating in the range 400–900°C., since its Nb/C ratio of 3:1 is much smaller than the 8:1 minimum ratio that is required to convert all the carbon into niobium carbide.

It can also be shown by calculation and reference to the Schaeffler diagram that metal of this composition would contain no ferrite. In square close-butt welds, however, metal from the electrode wire constitutes only about two-fifths of the weld pool. Element loss in the pool is known to be much less than that in the arc, so it is possible for the overall composition to be satisfactory. Partial compositions of actual weld metal were determined as follows:

	Analysis, %				
	C	*Si*	*Mn*	*Ti*	*Nb*
CO_2 Shielding	0·10	0·60	0·78	0·21	0·37
Argon–2% O_2 Shielding	0·09	0·57	0·75	0·20	0·44

They are very similar for the two shielding gases and show the great effect of dilution by fused parent metal.

Resistance of weld metal to intercrystalline disintegration was assessed by the standard copper sulphate test. Welds were made at a constant welding speed in CO_2, argon, and argon–2% oxygen, and duplicated specimens were tested in the following conditions:

(i) As welded
(ii) As welded +5 min at 650°C.
(iii) As welded +15 min at 650°C.
(iv) As welded +1 hr at 650°C.
(v) As welded +2 hr at 650°C.

This procedure was designed to compare weld metal deposited in the three gases by determining the periods of heating needed to produce grain boundary precipitation of chromium carbide—if this did in fact occur.

The specimens were boiled for 72 hr in a solution of 111 g/litre copper sulphate and 98 g/litre sulphuric acid.

The results of the test were assessed by bending the pickled specimens through 90° over a radius equal to three times the specimen thickness, the length of the weld being at right angles to the axis of bending.

No cracking was found in any of the test specimens, so that while no comparison between the three different gases was possible the results were reassuring with respect to the CO_2 process, since 30 min at 650°C. is the usual pre-test heat treatment.

Nimonic Alloys

Electrode wires of NC.82 and NC.90 were used for welding 16 s.w.g. Nimonic 75 and 90 alloys respectively. The wire diameter was $\frac{3}{64}$ in. in each case, and a single welding travel speed of 25 in./min was employed.

It was found necessary once again to restrict the arc voltage to the range 18–19 V to obtain the best bead appearance, and the current required to produce optimum penetration was found to be 90 amp with each material.

Weld Properties—Welds in the two materials differed greatly in form and surface appearance. Weld beads in Nimonic 75 were high and narrow, and were covered with a black oxidation product. The Nimonic 90 weld beads were flatter, with a tendency to fall away to one side, and here the scale had a greenish tinge. Isolated local elevations were found in these beads.

The presence of roughly spherical porosity was detected near the fusion line in the Nimonic 75 welds by radiographic examination. The Nimonic 90 welds were free from this defect. No other defects were revealed in either material.

Typical bead shapes are shown in Figs. 10 and 11, and these illustrate some of the comments made previously. The weld metal consisted of coarse grains with a pronounced dendritic structure. Although the weld beads were oxide covered, the inclusion content was not high, and no tendency for oxide film formation was evident. Heat-treatment of the Nimonic 90 welds produced some precipitation at grain boundaries in both the weld and the sheet.

Transverse tensile test pieces were machined from welds made in the two materials, the weld reinforcement and underbead being removed. The Nimonic 75 welds received no further treatment, whilst the Nimonic 90 welds were solution-treated for 20 min at 950°C., and were aged for 4 hr at 750°C., both treatments being followed by cooling in air. The results are shown in Table VII.

Table VII

Mechanical properties of transverse test pieces from Nimonic welds
(Fracture in weld)

Specimen		*U.T.S., tons/sq.in.*	*Elong. on 2 in., %*
Nimonic 75	Weld	43·5	12
		42·8	11
		43·0	12
	Sheet	50·0	35
Nimonic 90	Weld	69·3	11
		71·5	10
		67·0	8
	Sheet	78·0	30

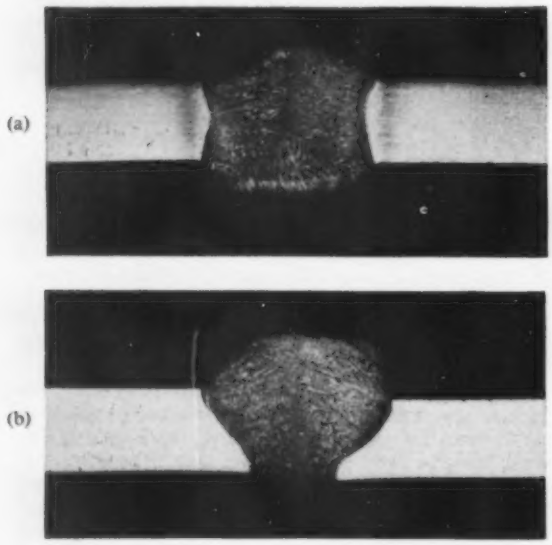
Fracture occurred through the weld in every specimen, and with Nimonic 75 some pores were visible in the fractures.

No tests were conducted at elevated temperatures, so no indication of high-temperature properties can be given.

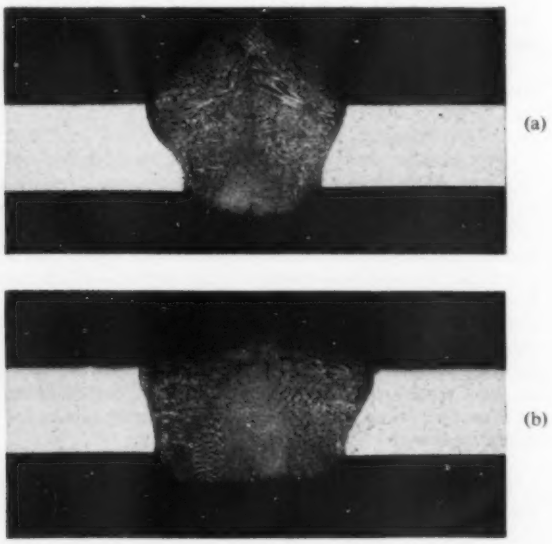
Chemical Analysis—To determine the transfer efficiency of the principal elements in the electrode wire, multi-run weld-metal pads were made at the current and voltage conditions previously used for welding. Samples were taken for chemical analysis from the upper runs of these pads and analysed, together with the NC.82 and NC.90 wires. The results were as follows:

Sample	*Analysis, %* *C*	*Si*	*Mn*	*Fe*	*Cr*	*Ti*	*Al*	*Ni*	*Co*
NC82									
Wire	0·22	0·39	0·98	0·66	19·4	—	—	78·4	0·08
Pad	0·16	0·37	0·87	0·66	19·4	—	—	78·5	0·05
NC90									
Wire	0·04	0·77	0·08	0·95	19·3	2·30	1·57	57·8	17·4*
Pad	0·16	0·81	0·08	0·89	19·4	2·10	1·01	58·1	17·2*

* By difference



10—*Macrosections of butt welds in 16 s.w.g. Nimonic 75. Welding speed 25 in./min*



11—*Macrosections of butt welds in 16 s.w.g. Nimonic 90. Welding speed 25 in./min*

The results for NC.82 are surprising at first sight, and it is difficult to reconcile them with the oxidized nature of the weld beads, since it would appear that little loss occurs by oxidation. It is conceivable, however, that oxidation would occur generally, *i.e.* without involving a selective attack on individual elements, and that the analyses show relative rather than absolute losses.

For the NC.90 wire some loss of titanium and aluminium was found, together with a considerable gain in carbon. The apparent gain in silicon and nickel is again an increase of proportion occasioned by a greater loss of other alloying elements.

Conclusions

A study has been made of the CO_2–shielded metal-arc, with the particular object of applying this consumable electrode process to the welding of sheet.

At the low currents (below 200 amp) employed in thin-gauge welding the use of a rapidly short-circuiting arc at 18–20 V is necessary to obtain weld beads of good shape and appearance. A constant-potential power source of suitable dynamic characteristics enables these low-current, low-voltage conditions to be operated.

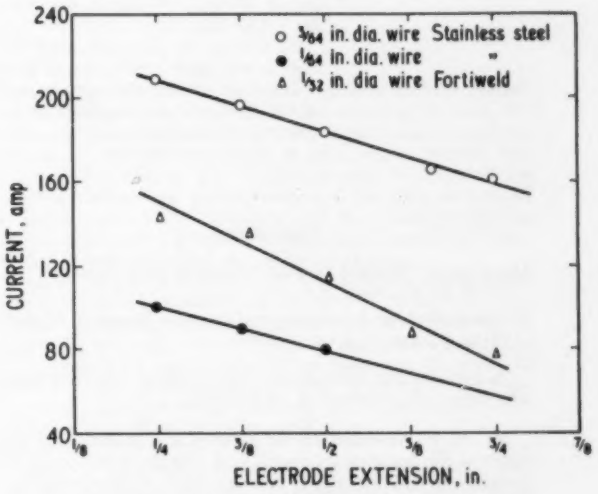
Welds in low-alloy steels exhibit satisfactory joint strength. The transfer efficiency of the elements Ni, Cr, Mo, and B across the arc is high and is not very different from that in argon–5% O_2. Heavy element loss is confined to the deoxidizers, silicon and manganese. The principal difficulties encountered are the 'peaky' nature of the bead and the occurrence of undercutting at welding speeds above 25 in./min. Reduction of the weld pool length might result in an improvement in weld contour, and the possibility of welding slightly downhill is worthy of investigation in this connection.

Welds in austenitic stainless steel exhibit excellent bead shape and appearance and possess a high degree of freedom from undercutting. The transfer efficiency of elements across the arc is high for Cr and Ni, and lower for the ferritizing and stabilizing elements Si and Nb. Carbon absorption occurs, but the effect of this and the element losses is minimized by the considerable dilution with fused sheet material.

Carbon dioxide is apparently not an ideal shielding medium for alloys of the Nimonic type, since appreciable oxidation of the electrode metal occurs. The oxidation products are unfused and from a scum on the weld pool, reducing its fluidity and causing irregularly-shaped bead formation. Nevertheless, welding is possible in this gas, and the composition of metal transferred across the arc is not markedly different from that of the original wire.

Appendix

The need for maintaining a constant electrode extension to obtain reproducible welding conditions is emphasized by the results plotted in Fig. 12, which show the effect of varying electrode extension on current at a constant wire feed speed and arc voltage. With increasing electrode extension, resistance heating in the wire assumes greater proportions, and less current is drawn from the power source to burn off the wire. In the welding tests described, electrode extensions of $\frac{1}{2}$ and $\frac{1}{4}$ in. were used for the $\frac{5}{64}$ and $\frac{1}{32}$ in. dia. wires respectively.



12—*Effect of electrode extension on welding current at constant 200 in./min wire feed speed (18–19 V arc voltage)*

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1. G. R. ROTHSCHILD: *Welding J.*, 1956, vol. 35, p. 19.
2. R. E. JAHN and L. M. GOURD: *Weld. Metal Fab.*, 1956, vol. 24, p. 368.
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DISCUSSION AT THE SYMPOSIUM ON:

Fatigue of Welded Structures

A Symposium on the Fatigue of Welded Structures was held at Cambridge University from 29th March to 1st April, 1960, jointly organized by the British Welding Research Association and the Engineering Department of the University.

Eleven papers were presented for discussion; these were published in the March and April 1960 issues of B.W.J.

The discussion on three papers, at Sessions I and II under the Chairmanship of Dr. R. Weck, are presented here. The discussion at the remaining sessions will be published as it becomes available.

Session I

The Fatigue Strength of Butt Welds in Mild Steel*
By R. P. Newman

A Possibility for Increasing the Fatigue Strength of Butt Welded Joints† *By W. Gilde*

In introducing their papers, the authors included some new items of information, as follows:

Mr. R. P. Newman: In the paper it is suggested that the notch at the junction of a weld and a backing bar could be as severe in its effect as the poorest shape of reinforcement. This was a tentative observation, inasmuch as results from bending tests of small diameter pipes were taken to indicate what might be obtained from flat plate specimens under axial loading. Tests now in progress with such specimens are showing that the prediction will not be very far out. It is quite certain that the mode of failure shown in Fig. 6*a* holds good. It appears then that the joint in Fig. 6*a* must be bracketed with that in Fig. 4*b* in terms of fatigue performance; and it must be noted that this would apply even when the backed joint is made under the most favourable conditions—in the down-hand position.

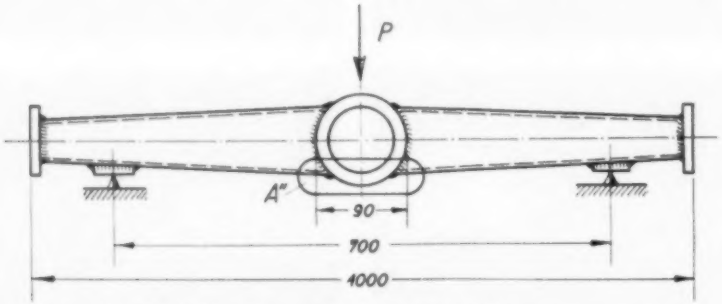
Dr. W. Gilde: Since writing the paper we have made experiments with larger specimens. Figure *A* shows the axle of a motor car. The surfaces in the area of the brackets were sand-blasted and a coating of the plastic material EGK19 was applied. The number of cycles of pulsating bending of the uncoated axle, under the loading shown, was 1,350,000, whereas the coated axle survived over two million cycles without failure. Also in the case of fillet welded members we have observed an increase of fatigue properties. The beam shown in Fig. *B* has a fillet-welded attachment. After this area had been cleaned with a wire brush, a coating of EKS11 plastic was applied. As indicated in the diagram an increase in endurance of 50% is achieved. We are pursuing these tests so as to establish the increase of fatigue strength.

Dr. R. Weck: Before I invite discussion of these two papers perhaps Dr. Gilde would explain the symbols for electrode types given in Figs. 2, 3 and 4 of his paper.

Dr. Gilde: Electrode Kb IX–Xs is a low-hydrogen type; Ti VIIIs a rutile type; Es VIIIs an acid type, and Ti VIIm an electrode giving large droplets which is used primarily for making root runs.

Mr. E. M. Lewis (W. S. Atkins & Partners): I must confess that I had never suspected that covering a welded joint with a plastic would have an effect on fatigue strength. I had hoped that Dr. Gilde would offer an hypothesis to explain this most interesting phenomenon and I would ask him if he is able to do so.

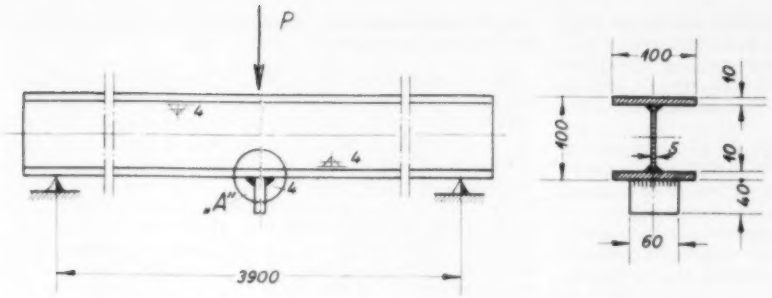
In the meantime, two thoughts on this matter have



Surface at A	*Plastic Coating*	*Load*	*Cycles to Failure*
As-welded	—	Pulsating bending	1,350,000
Sand-blasted	EGK 19	σ_{bo} = 12 kg/sq.mm σ_{bu} = 3 kg/sq.mm	> 2,600,000

A—*Motor car axle*

* *Brit. Welding J.*, 1960, vol. 7, p. 169.
† *Ibid.*, p. 208.



B—*Beam with fillet welded attachments*

Surface at A	*Plastic Coating*	*Load*	*Cycles to Failure*
As welded	—	Alternating bending	1,050,000
Wire-brushed	EKS 11	$\sigma_{bw} = \pm 15$ kg/sq.mm	1,550,000

occurred to me. The first is that, since the Young's Modulus of plastics is very much smaller than that of steel, one would not expect the plastic coating to carry very much stress and so relieve the steel part of any load. If, however, the surface of the steel developed small cracks that were bridged by the coating, it would appear that, in spite of the low modulus, this bridging of the cracks has a beneficial effect. It would be interesting to know if Dr. Gilde has any plans for comparing the behaviour of spring steel with and without a decarburized surface and with and without the plastic coating.

The other thought that occurred to me was that the coating gave protection against atmospheric corrosion. We all know examples of structures exposed to atmospheric corrosion not lasting as long as one might expect them to do from laboratory evidence. Perhaps the protection against corrosion and the inhibition of oxygen are important influences. I would be glad if Dr. Gilde could enlarge on his thoughts as to what lies behind his most interesting observations.

Dr. Gilde: Firstly I must say that we have no firm ideas on the reason for the influence of the plastic coating. I have referred to the paper by Benedicks, who studied the influence of fluids; these have no Young's Modulus. A plastic is a fluid, with a high toughness.

So far we have tested only mild steel, and it is clear that this work can be greatly extended. We are, in fact, only at the beginning, and we submitted the paper so as to obtain a discussion that could be useful to us in planning future work. With regard to corrosion, some colleagues in our Institute thought at first that the influence of the plastic coating was due to the exclusion of oxygen. But it has been shown that not every coating is able to exclude oxygen, the effect of which, therefore, cannot be large. The plastic Polykoll contains 40% Kaolin and is less impervious than the epoxy resin KGK19. The latter material, however, gives the lower fatigue result of the two.

Dr. J. S. Blair (Stewarts and Lloyds Ltd.): I would like to say a word first about Mr. Newman's interesting paper. I am continually bedevilled by the word "reinforcement". The surest way to weaken a weld is apparently to put a "reinforcement" on it. I know this word has been built up in the past because it was thought that one achieved strength by adding metal. I hope we know rather better these days. I would like to suggest that it is a thoroughly misleading name; could we not do something to kill it? Cannot we call this lump on either side of the weld something like "overfill", or at least something which implies that it is a bad thing?

With reference to Dr. Gilde's extremely interesting paper, I am under the impression that galvanizing has been found to be beneficial on fatigue specimens. I cannot now quote any relevant data; perhaps somebody else can. But it does seem that there must be something in this question of the exclusion of oxygen. It is interesting to note, for example, that the media in Table I which cause a positive change of strength are fluids in which there is little free oxygen. I admit, as Dr. Gilde has said, that all of the plastics exclude the atmosphere, and yet they do not all give the same results. It may be that the oxidation effect is only a small part of the whole story, but it would be interesting to hear the views of a corrosion expert.

Many of you will know that epoxy resins are used for the lining of tubing in the oil industry. Such tubing is not usually liable to failure by fatigue; some failure shave, however, occurred, and it would be useful to know if the introduction of epoxy resin linings has been observed to reduce the failure incidence. It would be interesting if their use as an anti-corrosion measure did, at the same time, improve the strength of the material.

Mr. W. E. Cowley (Associated Ethyl Co. Ltd.): Mr. Newman has said that the two butt joints in Fig. 4 of his paper have the same fatigue strength when they are ground; the effect of the shape of the weld metal and the heat-affected zone on the fatigue strength of this type of joint must therefore be very small. If this is so then the poor contour chosen in Fig. 4*b* must be responsible for the low fatigue strength; with a better contour the result would probably have approached that of Fig. 4*a*.

With respect to Dr. Gilde's paper, we have experienced failures in mild and stainless steels and in Ni–Cr–Mo alloys, in atmospheres; *e.g.*, chlorine-saturated sulphuric acid and sodium-nitrogen, where the full fatigue strength of the material has obviously not been realized. We have found that if the metal surface is protected against the atmosphere there is a much better fatigue performance. The environmental effect on the fatigue strength of a metal or alloy can be very great (for instance the fatigue strength of stainless steel in sodium-nitrogen atmospheres can be reduced by 95%) and is one of the most important aspects of fatigue requiring further study.

With respect to the effect of resin, plastic, or rubber coatings on fatigue strength, one has to consider the nature of the metal surface and the possible chemical action the surrounding atmosphere may have on it. For instance, the rates of corrosion of steel in perfectly dry air or perfectly de-aerated water are negligible. It is important, therefore, to establish the mechanism whereby coatings influence fatigue strength. Dr. Gilde's results given in Table III show that the higher the resistance of the coating to water and gas permeation the greater is the improvement in fatigue strength. It is claimed that butyl rubber coatings are more effective than natural rubber coatings. Here again the same criterion holds. It would be interesting if Dr. Gilde could carry out some further work using Zakophan Si14E, a coating used in Germany, which has excellent resistance to water and gas permeation and very

good wetting properties on steel surfaces compared with the resin coatings he used, which have relatively poor wetting properties. Resin and rubber coatings also have very good damping properties. This may play a part in improving fatigue strength, perhaps in conjunction with the elimination of notch effects.

It would be interesting to establish the effect of surface preparation before the application of a coating. Dr. Gilde just wire brushed the surface before applying the coating, thus leaving a surface layer with a high oxide content. We have found that best results are obtained by using a shot-blasted surface. The use of coatings on passive phosphated surfaces is widespread; does phosphating give a further improvement in fatigue strength?

Dr. Gilde: I do not know Zakophan Si14E, but it could be obtained for trial.

Mr. Newman: Mr. Cowley has correctly interpreted the point I was trying to make about the influence of "overfill" shape. What we have done is to test a range of joints with different geometries, to show that this is not an unimportant factor when transverse butt joints are subjected to fatigue loading. In fact, the joint in Fig. 4*b* is not unrepresentative of what is obtained in actual shop welding with the submerged-arc process. We have taken care to eliminate any apparent bias by showing that good results are derived from submerged-arc welding if one takes precautions with respect to "overfill" shape.

Mr. Cowley referred to the method of preparing a steel surface for plastic coating, and I would also like to ask Dr. Gilde to comment on this. He has stated that mechanical means of cleaning the surface were used; if by this he does, in fact, mean shot-blasting then it is not impossible that some of the improvement in fatigue properties was gained in this way. In regard to the corrosion aspect of Dr. Gilde's tests, would not the presumably short period of testing have to be considered, particularly in connection with the permeability of the plastics?

Dr. Gilde: The specimens were sand-blasted. We have made some experiments to study the effect of this method and we find that sand-blasting by itself has only a very small influence. I agree with Mr. Newman about the time effect. The individual tests lasted, say, for one week. Over this short period I do not think that slight differences in water resistance would be important. But it is possible that in one year there would be an effect; we just do not know at this early stage of the work. Dr. Blair mentioned galvanizing. When this is done the steel is given a very good surface preparation, and I doubt if the galvanizing of butt joints would be successful.

The changes in fatigue strength shown in Table I cannot simply be interpreted. For example, whilst it is shown that 10% NaOH results in an increase of +15%, it is known that lower and higher concentrations of NaOH result in a decrease of fatigue strength.

One interesting application of plastic coating has recently been made in connection with racing cars. The driver's seat was actually part of the fuel tank which, it was found, developed cracks. By coating the tank these failures have now been prevented.

Dr. W. B. Carlson (Babcock & Wilcox Ltd.): I would like to support Dr. Blair's plea for a renaming of the "bulge".

In so far as Dr. Gilde's paper is concerned, I would suggest that if one made a U-notch specimen and filled the notch with a plastic having a good adherence to the steel, then under tension and compression loading, hydrostatic tension and compression would almost certainly develop in the plastic and so ameliorate the conditions in the notched steel. This has not been checked by experiment but I think some such action could be part of the explanation for Dr. Gilde's results.

Dr. A. Nicholson (United Steel Companies Ltd): Wadsworth and Hutchings[1,2] have tested a number of metals—copper, aluminium, and iron—in air and in high vacuum, and they have shown quite clearly that there is a significant effect due to atmosphere in all three metals. There is no effect in gold. It seems to me that the epoxy resin is very probably acting as a barrier to atmospheric attack. The suggestions of Wadsworth and Hutchings in regard to possible mechanisms of atmospheric-corrosion/fatigue attack are based on the fact that it is possible for the air to reach the bottom of the crack within half a cycle of stress, even at high frequencies of 100 c/sec or more. Their suggestions are: firstly, that oxygen or water vapour is attacking the highly stressed metal right at the base of the crack and therefore accelerating the spreading of the crack; or alternatively, that atmospheric gases chemisorb on the freshly exposed faces of the crack and prevent it from healing on the compressive half cycle, at the same time setting up additional stress at the notch because of the extra layers of molecules in the crack.

I was associated with some work at Birmingham University[3] on the fatigue behaviour of aluminium alloys. We observed a substantial increase in fatigue life *in vacuo* compared with normal atmospheric tests (push-pull) and found that the reduced life in air could be related to the effect of water vapour. The influence of coatings was briefly studied, and with butyl rubber, which was the best from the point of view of impermeability to water vapour, we obtained an increase of life of the same order as that obtained from tests in high vacuum (10^{-6} mm Hg).

Dr. Gilde: What was the increase?

Dr. Nicholson: The alloy in this case was Duralumin which survived 7 to 10 times the life in air. The atmospheric tests were done to give fatigue lives of the order of 10^5 cycles. But Wadsworth and Hutchings' work showed the effect over a range of endurances of about 10^4–10^7 cycles.

Dr. Gilde: It would have been interesting to know, not only the increase of life, but also the increase of strength. I have quoted the Gough and Sopwith results for a vacuum of 10^{-3} mm Hg, and the increases of strength are not large. Perhaps better results would have been shown for a vacuum of 10^{-6}.

Dr. Nicholson: I cannot remember exactly, but I believe that for Duralumin an increase of 2 tons/sq.in. at 10^7 cycles was indicated. I can, however, obtain confirmation of this if there is some interest in having the figures.

Mr. J. E. Russell (English Steel Corporation Ltd.): Dr. Gilde's results do support those we have obtained on Wöhler specimens coated with plastics. Indeed, there is a significant improvement in the life of this type of specimen merely by coating it with cellulose tape. This is a minor kind of experiment, although it does show what is possible. But frankly my main worry about the influence of coatings is that once a flaw develops in the coating the fatigue life is very drastically reduced, because the attack through that flaw is very highly concentrated. I feel that Dr. Gilde's tests have not gone far enough, in that the fatigue limit of the coating itself is significant. If a fatigue crack were to occur in the plastic one might expect the steel to fail rapidly.

I would now like to put two questions to Mr. Newman, the first one on the question of hammer peening of welds. We do know that the introduction of compressive stress by mechanical work, such as rolling or hammering, has a beneficial effect on fatigue life. There are suitable hammers that could be adapted to the peening of welds, and it would be of interest to consider whether the treatment of the edge

of the reinforcement would similarly increase the fatigue performance of welded joints. The second question is perhaps an obvious one and possibly a little loaded. In a cylindrical pressure vessel the longitudinal stress is much lower than the circumferential stress; for a thin-walled vessel it is about half the circumferential stress. The implication of his work is that if a pressure vessel were to be made by forging or drawing tubes and welding them together with transverse seams, it would have significantly better fatigue properties than one made by rolling up a plate and welding it longitudinally. As this may have some commercial implications, I would like to know if Mr. Newman, speaking on behalf of B.W.R.A., would substantiate this conclusion.

Mr. Newman: We have not carried out any extensive research into the effect of hammer peening but we have used the technique in the laboratory to help keep pieces of equipment together where fairly severe fatigue loading of joints has been involved. And we have obtained good results in the sense that we have kept the equipment working for longer than it would otherwise have done. Dr. Guerrera might be able to tell us something of a much more comprehensive investigation carried out in Italy where a special, air-operated peening tool has been used for the treatment of butt and fillet welded joints in mild steel; this has resulted in marked increases of strength. This work is well documented and the results could, I am sure, be made available to people who are interested.* We ourselves have never felt any great pressure from industry to investigate the process, possibly because there is an additional, and perhaps significant, labour cost involved.

Speaking for myself on the pressure vessel problem—I will allow my colleagues collectively to put me right and speak for the B.W.R.A. if they wish—I do not think one could uphold the statement that a pressure vessel made with only circumferential seams must automatically be better than one made with longitudinal seams. Usually pressure vessel welds are radiographed, and it follows that usually the welds are dressed. From these two considerations it follows also that welds made either circumferentially or longitudinally would be good-quality welds, and I do not think that we can distinguish from the results of fatigue tests any important differences between the two types if surfaces are dressed and if the welds are made to class 1 radiographic standards. If, on the other hand, these considerations do not apply, and if the welding is not carried out to a reasonable standard, then the kind of variations of strength noted in the paper could be taken into account. These variations, however, are more marked for high endurances, and again I think this tends to remove this question from the field of pressure vessels.

Dr. A. A. Wells (B.W.R.A.): There is one other point in this connection, arising out of experience with fabricated pipe bends; longitudinal score marks are quite as important as weld reinforcements with regard to fatigue crack initiation. In the case of the forged cylinders one would require to be certain that longitudinal score marks were absent, if the absence of weld reinforcement were to be truly exploited.

Dr. Gilde: We also thought, as Mr. Russell does, that a crack in the plastic coating would have a serious effect, but have found that this is not so. With one of the motor car axle specimens a fatigue crack developed in the plastic after a short time, the crack being located in the area of the covered weld. We expected rapid failure of the axle but this did not happen. It seems that between the plastic and the metal there is a metal-plastic layer. It is known that if one applies an adhesive to a metal part then in many cases the destruction of the part does not destroy the adhesive; parts of the metal are in fact torn out. We do not know very much about this layer between metal and adhesive, but it is possible that a crack in the coating would stop at this layer, although we are not certain about this.

It was also thought that the strength of the plastic had an influence on the fatigue strength of the whole specimen. This is not so. The Polykoll plastic is a polyester with 40% Kaolin; this material in itself does not have good strength. We thought that if we had a polyester with glass fibre, with a strength of 40/50 kg/sq.mm we would get better fatigue results, but actually the results were worse. Further, we now know that it makes no difference if one has a coating thickness of $\frac{1}{2}$ mm or of 3 mm.

Mr. E. Lister (Stewarts and Lloyds Ltd.): The fatigue strength figures for butt welds given by Dr. Gilde are lower than those indicated by Mr. Newman for mild steel. The figures are low enough, and differences of 1 ton/sq.in. are becoming significant at the low stresses quoted. It would be a very useful thing if at this Symposium the various experts would get together and give us an agreed figure for the fatigue strength of butt welds.

Dr. Gilde says that low-hydrogen electrodes give better fatigue strength than rutile covered electrodes. Mr. Newman in his paper does not mention the types of electrode he has used and I wonder if he would like to comment on any effects he might have observed that were attributable to electrode type. Authors of other papers to follow seem to suggest that there are no such effects.

Returning to the influence of coatings and environment; we have recently done some rotating cantilever fatigue tests on high-tensile steel, and have compared results obtained in air with those obtained from tests in which the gauge length was in water. At high endurances the effect of water was to reduce strength to about 30%, but the shape of the fatigue curves was such that if tests had been done at higher stress levels one might have expected water to give a beneficial effect. Presumably the cooling effect at very high stresses plays a part, whereas at long endurances one is concerned with corrosion.

Mr. Newman: I have said in my paper that fatigue results for butt welds tend to be endemic. There are many reasons for this, and variation of weld geometry is perhaps the most obvious one. However, testing technique is also an important factor. One cannot make a strict comparison between alternating bending and the axial load test that is more commonly used, and in general I think Dr. Gilde's results are reasonable. Regarding the influence of the electrode, I place this with the consideration of the influence of weld geometry. For transverse welds there is not a significant difference between low-hydrogen and rutile electrodes, provided that the welder is experienced with the low-hydrogen type and does not produce under-cutting. With longitudinal welds, however, surface roughness enters into the problem, and on this count low-hydrogen electrodes are probably not as good as other types.

Mr. S. Wise (British Railways Research Dept.): I am extremely interested in Dr. Gilde's experiments, but there may be a danger in forgetting the existence of defects in the welds. With significant defects, say hot-cracking, will not fatigue strengths be exactly the same irrespective of whether or not the joint is coated with plastic? If this is so it may be difficult in design to take account of the influence of the plastic coating, unless one has extremely good non-destructive testing techniques. In connection with the environmental aspect, I would like to suggest that the exclusion of the atmosphere is much less important than neutralizing or removing altogether the adsorbed gas layer that exists on the surface of every metal. If you can remove this layer, as might possibly occur in high-vacuum testing, or if you can neutralize it, as might be happening with these

* Further details will be published in the August B.W.J.

plastic coatings, this could be responsible for the increased fatigue performance that is observed under these conditions.

Dr. Gilde: Mr. Wise is right to draw attention to defects. In our tests the welding of the specimens was controlled and they were examined radiographically.

Dr. R. G. Baker (B.W.R.A.): Dr. Gilde has presented very strong evidence that the fatigue life of a weld can be improved by coating it with plastic. It has been suggested subsequently in discussion that such protection may be effected by the exclusion of all corrosive media from the surface, *e.g.*, adsorbed gas etc. If this is indeed the case, while not wishing to pose as an expert on corrosion, I would like to suggest three possible protection mechanisms:

(i) If the plastic coating were completely continuous with no pores, it would completely blanket the surface from the ingress of gas, moisture, etc. However, this would not seem to be the only mechanism since Dr. Gilde has stated that the more porous of the coatings he has examined have sometimes been the more effective in prolonging the fatigue life.

(ii) If the coating contained amphoterric molecules these might well form a highly adsorbed monolayer on any free metal surface, thus providing efficient protection. There is some evidence here that such molecules do in fact prolong fatigue life; for example if a fatigue specimen is coated with oil.

(iii) If the plastic contained corrosion inhibitors these might prevent corrosion of any free metal surface.

As a corollary to these ideas it might be expected that, if corrosion is responsible, base-metal coatings (relative to steel) should prolong life since any gaps in them would be cathodically protected, but that noble coatings should result in a decreased life unless they remain absolutely perfect, since accelerated anodic attack would occur at any faults in them. There is some evidence to show that galvanizing improves the fatigue life, although from the evidence available it is difficult to establish rigorously whether or not this is due to its effect in preventing corrosion. There is also some evidence to suggest that sprayed chromium and nickel coatings give rise to very poor fatigue life, extensive corrosion taking place beneath the coatings. Such coatings, though more noble than steel, contain many defects where the steel is exposed.

The above ideas would also lead one to expect that testing *in vacuo* should increase the life, and again experiment suggests that it does so.

I would also like to ask Dr. Gilde exactly where the point of crack initiation occurred in the plastic coated specimens; *i.e.*, was it at the edge of the reinforcement or at the edge of the plastic, or did it vary?

Dr. Gilde: In most cases the fatigue crack was in the heat-affected zone.

Perhaps at this point I should mention that the plastics were applied with a brush.

Dr. K. Gardiner (B.W.R.A.): Dr. Gilde has shown the effect of covering the weld bead with a plastic coating, and Dr. Baker has further emphasized the effects of surface condition. It appears to me that the protection afforded by the plastic coating must in some way be related to the average modulus across the surface. The work of Zener[5] and his colleagues in America is exemplified by the formula:

$$\tan d = \frac{Mu - Mr}{Mm} \cdot \frac{Wt}{1+(Wt)^2}$$

Here tan d is a measure of the internal friction or damping in the specimen under consideration. Mu is the unrelaxed modulus, *i.e.*, one measured 'instantaneously' by some form of impact technique. M_r is the relaxed modulus, as measured by conventional 'slow' tests. Mm is the geometric mean of these two moduli. Hence anisotropy of moduli, and Poisson's ratio cancel out. Wt relates to the frequency of the process under consideration.

This formula could well be employed *via* some sensitive ultrasonic probing to measure tan d, the angle of lag relating stress and strain during cycling; thus the 'effective' surface modulus could be estimated.

Clearly the 'effective' surface modulus is closely related to any rupture process which initiates at the surface, as in the cases of weld failure suggested today.

These mathematics probably appear to have scant relevance to the engineering problems of real structures but I was moved to work out this suggestion from the close parallel with the automobile industry. Here Rubberoid coatings are used not only for the protection of underbodies but also to reduce drumming and travel noise generated in the thin mild steel sheets.

In conclusion I would add that Dr. Gilde's technique can be of great value in fatigue applications so long as the applied plastic surface remains truly integral with the base metal.

Dr. Nicholson (in a further communication): Dr. Gilde notes that Gough and Sopwith found a 5% increase in the fatigue stength of steel when tested *in vacuo* (10^{-3} mm Hg). More recently Wadsworth[1] has reported a much greater effect (vacuum$\simeq 10^{-6}$ mm Hg) in both high- and low-carbon irons. This is not surprising since, over the whole S/N curve, fatigue life has been found to increase progressively with decreasing atmospheric pressure with no sign of levelling off at the lowest limits of pressure studied.[2,3] Precise comparisons of Wadsworth's data with that of Dr. Gilde is not possible since the former refer to tests at constant strain amplitude. For a fatigue life of 2×10^6 cycles, Wadsworth's S/N curves show approximately 45% increase in strain amplitude *in vacuo*. Impurities and small alloying additions can profoundly effect atmospheric fatigue attack.[2,3,4] For example, two batches of copper of different purity gave ratios of life-in-air/life-*in-vacuo* (10^{-6} mm Hg) of 1:10 and 1:20 at a given strain amplitude.[2]

I think it is quite probable that atmospheric corrosion fatigue may explain Dr. Gilde's results. The difference in behaviour between notched and welded specimens may arise from a difference in susceptibility to atmospheric corrosion fatigue caused by the weld metal.

Details of the rubber coating work on aluminium alloys, which I mentioned in the discussion, are as follows:

Material	*Semi-Amplitude of Stress, tons/sq.in.*	*Tests in Air*		*Tests in Dry Nitrogen*		*Tests with Butyl Rubber Coatings (approx. 0·15 mm thick*	
		No. of Tests	*Mean Life*	*No. of Tests*	*Mean Life*	*No. of Tests*	*Mean Life*
D.T.D. 683	19·5	12	$1{\cdot}18\times10^5$	6	$7{\cdot}25\times10^5$	9	$9{\cdot}13\times10^5$
Duralumin	20·5	6	$6{\cdot}64\times10^4$	6	$5{\cdot}42\times10^5$*	6	$7{\cdot}03\times10^5$*

* Statistical analysis shows that differences under these two test conditions are not significant.

The tests were carried out in push-pull at zero mean stress and a frequency of approx. 150 c/sec. The gauge length of all specimens was abraded in the longitudinal direction with fine emery paper to remove circumferential machining marks.

Other tests with butyl rubber coatings have shown that the improvement over normal atmospheric tests is fairly constant in the range 10^4–10^7 cycles to failure.[3]

In the case of the rubber coatings there is virtually no mechanical support of the surface. Moreover, if the rubber is applied and then stripped off again before testing, a normal atmospheric fatigue life is obtained. This suggests that if an absorbed film is deposited from the rubber or its solvent it appears to have little effect. I think it would therefore be interesting to compare the effect of rubber coatings on the fatigue behaviour of welds with that of resins.

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Session II

The Fatigue Strength of Welded Joints in High Strength Steels* *By J. E. Stallmeyer and W. H. Munse*

Professor W. H. Munse presented the paper, and in his introductory remarks he stated that for structural work in the U.S.A. the main interest in using high-strength steels was probably associated with loading conditions where high mean stress due to dead load was involved. In other circumstances, if the loading was cyclic, it was considered that there was little difference between mild and high-strength steels from the standpoint of fatigue strength. Bridge specifications reflected this belief, in that allowable working stresses for floor systems were the same for all steels. For large bridges, however, the favourable use of high-strength steel for main members had been suggested, because dead loading represented the major part of the overall loading. An example of the application of this idea was seen in the design of the new Carquinez Straits bridge in California, in which mild steel, ASTM A-242 steel and T.1 (quenched and tempered) steel were all used.

Mr. R. P. Newman (B.W.R.A.): The paper well illustrates the magnitude of the problem of winning better fatigue properties from welded high-tensile steel. This problem contains several formidable items:

(i) The parent metal is more notch sensitive than mild steel. Anything like pro-rata increases of fatigue strength with tensile properties depends then on the absence of notches. In the context of engineering structures this can only remain a whimsical notion
(ii) If weld-metal is matched with base-metal tensile properties, one gets an increasing sensitivity to defects
(iii) But assuming no notches, either in parent material or weld metal, can one in fact get very much farther before one meets two more barriers in the form of the fatigue strengths of heat-affected zone and black plate—in whatever order they might choose to turn up?

It is clear that the prospects of gaining greatly improved fatigue properties will depend upon some critical work on what appear to be limiting boundaries. In the meantime the engineer seeks his solutions to application problems as best he can, with a growing realization that he is somewhat confined. It is understandable that the engineering approach has almost entirely been concerned with the reduction of notch effect, and, given laboratory conditions, some rewards can be obtained in this way, even if they are limited in their application. We might consider, for example, another summary of the kind shown in Fig. 2 of the paper, again for the performance of transverse butt welds at 2×10^6 cycles, tested under a stress ratio of $f_{min}/f_{max}=0$ (Fig. *C*).

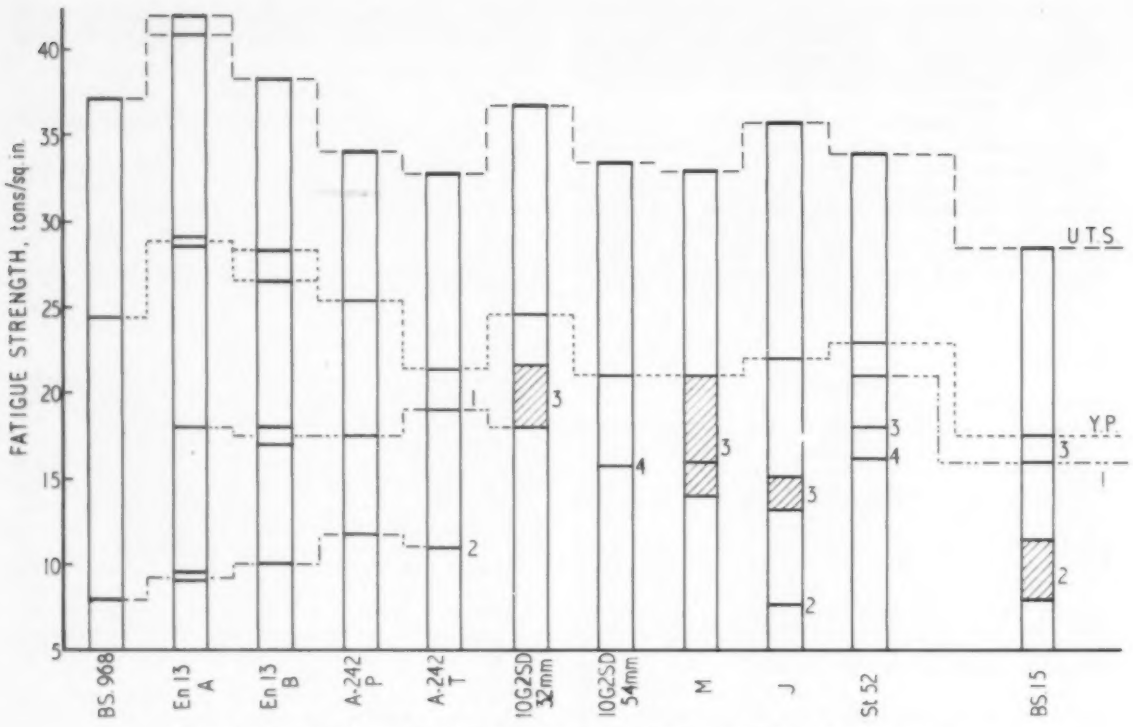
This diagram includes one or two of the materials referred to by the authors, but it is more restricted in that tensile strengths are in the range 30–42 tons/sq.in.† The top dashed line joins the tensile strengths and the second dashed line the yield strengths. Set up on the right-hand side are the values for BS.15 mild steel. First one can compare reported fatigue strength values for the transverse joints with reinforcement left on—the results at level 2. The materials concerned are BS.968 (0·23% C, 1·5% Mn), En 13 (0·18% C, 1·5% Mn, 0·30/0·50% Ni, 0·1% Cr, 0·2% Mo), ASTM-A242 steel (as in the paper under discussion) and *J* steel (the Japanese steel referred to in the paper). In the 'as-welded' form these materials give fatigue strength values that coincide closely with the known limits for mild steel.

For En 13, A-242, and steel 10G2SD we can compare black plate properties (10G2SD is a Russian steel 0·14% C, 1·0% Si, 1·6% Mn, 0·30% Ni, 0·30% Cr, 0·2% Cu). The fatigue strengths of the black plate are in the range 17–19 tons/sq.in., compared with 16 tons/sq.in. for BS.15. In terms of the fatigue/tensile strength ratio, only A-242, T grade, matches BS.15, and this grade is itself little more than a mild steel. Again, only the T grade A242 steel approaches BS.15 performance in respect of the fatigue/yield strength ratio and this ratio diminishes as yield increases. And yet it is quite possible that if they are tested in polished bar form one would see a better reflection of the tensile properties of these materials. To what extent then are we concerned not only with notch-sensitivity, but also with carbon and alloy impoverishment of the surface?

Finally, one can gain some impression of the degree of improvement that is possible with these materials—at least, in so far as butt welds are concerned—by referring to the 3–4 area of the diagram. These results relate to joints with surfaces machined or ground, or, in two cases (level 4) to joints made especially carefully with respect to reinforcement shape. This is, if you like, the maximum amount of ground that the engineering approach is able to cover. Although it appears that the gap between the 'as-welded' joint and the black plate strength can effectively be closed, it must be emphasized that joint quality in the 3–4 region is critical. Thus, absence of weld defects and the care with which grinding and machining are carried out will be of the greatest importance. Whether the control of reinforcement shape too, is something one could visualize as practicable outside of the laboratory must be open to doubt. In so far as butt welds are concerned, therefore, improved high endurance fatigue properties at present demand a degree of consistent control in welding that is attainable possibly only with automatic welding. And unless the most careful surface dressing could be guaranteed, there would appear to be a further restriction to continuous, longitudinal joints.

* *Brit. Welding J.*, 1960, vol. 7, p. 281

† The diagram is based on a survey of the literature [1–6], rather than on original data.



1. Black plate 2. As-welded butt joints 3. Machined or ground butt joints 4. Controlled reinforcement butt joints

C—Static and fatigue properties of plain plate and transverse butt welds in high tensile steels. (Zero-to-tension axial stress cycle, 2×10^6)

Having arrived at the conclusion that high-tensile materials might be shown in the best light when the joints are continuous, longitudinal joints, it is of interest to consider the behaviour of a plate-girder type of specimen constructed in this way. We are now engaged upon an investigation of this kind, and for BS.968 material the results to date are certainly quite promising.

Dr. R. Weck: The story we have heard from these two speakers is, I think, a rather dismal one. If I were not an engineer but a metallurgist I would consider this a challenge. One wonders whether the development of the so-called high-strength steels has not been based on what is almost a philosophical misconception; namely, that to obtain higher fatigue strengths a material must first be produced with higher yield and tensile strengths. It is perhaps possible that tensile and yield strengths are one kind of property and fatigue strength, particularly of welded joints, is an entirely different kind of property. I cannot help wondering whether we should not attempt to put the development of these materials on a new basis, by not striving to improve tensile strength but by striving to improve fatigue strength irrespective of tensile strength. I hope we shall hear something more of this line of thought from the metallurgists in the audience.

Mr. S. Wise: I would like briefly to describe some development work we have been doing on butt welds in high-tensile steel, and I think it will be found that the results are complementary to those already given by Professor Munse and Mr. Newman. This development work concerns welded railway rails of 50 tons/sq.in. tensile strength, 0·5% C, 1·0% Mn. Three methods of welding rails are in use, flash-butt welding thermit welding and metal-arc welding; a large number of fatigue tests to investigate the relative merits of these processes have been carried out. The strength values I shall quote refer to 5×10^6 cycles of uni-directional bending, producing substantially zero-to-tension stressing of the foot of the rail.

With new rail the fatigue strength can vary between 15 and 20 tons/sq.in., depending on the rail condition, the higher strengths being observed for rail taken straight from the mills. Flash-butt-welded joints give the same strength as the rail in which they are made and failure seldom occurs in the joint. A new development of the thermit process gives strengths ranging between 10 and 14 tons/sq.in. for joints in the 'as-welded' condition; the reason for this variation is not known. Finally, tests have been done on metal-arc welded joints. These are made according to technique originally devised by Philips Electrical Ltd., but which, in view of the development carried out by British Railways, I now prefer to call the Hardy-EW method. Square-ended rails are set up to a $\frac{3}{8}$ in. gap and with a steel backing member at the foot which is, in turn, supported by a copper backing. The electrode is held vertically and the welding is not interrupted for deslagging after the first two or three runs. Copper side pieces form a dam to contain the molten metal. After welding, the backing member is removed and the weld in the foot is ground to as good a finish as is possible, bearing in mind that space underneath is restricted since the job is done in the track.

The fatigue strength of such joints is 11–12 tons/sq.in. When we first started, we used an ordinary low-hydrogen electrode of 35 tons/sq.in. tensile strength and obtained a fatigue value of $10\frac{1}{2}$ tons/sq.in. Currently we are using a 45 tons/sq.in. low-hydrogen electron which increases this

value by about 1–1½ tons/sq.in. But with electrodes of 50–60 tons/sq.in. tensile, no measurable improvement of fatigue properties is evident. One or two isolated results to the right of the scatter band indicate what we might get if everything was in our favour, but on the whole the average result is always lower. The reason for this is undoubtedly associated with the influence of defects, and we have done a good deal of work with the ultrasonic method so as to be able to check the presence of defects in welds of this kind. By correlating defect incidence and fatigue failure we find generally that small slag inclusions are not important, but lack of fusion at the bottom edges of the weld and hot-cracking are both of vital importance, even if they occur as very small defects. The procedure has been modified to eliminate lack of fusion as far as possible, and we have noted that hot cracks tend to be associated with a particular electrode.

It is rather interesting that Mr. Newman said one of the limiting factors in obtaining higher fatigue strength of welds was the fatigue strength of the material. It will be seen that whereas we now have fatigue strengths of 12 tons/sq.in. we do have the limitation that the fatigue strength of the rail after exposure to corrosion is no more than 15 tons/sq.in. We have, therefore, only a very little way to go. And what appears to be quite certain is that there is no hope in using a higher-strength electrode unless it can be guaranteed that the deposit is free from any defects whatsoever; this seems to be too idealistic a requirement ever to be realized.

Professor W. H. Munse: I would certainly agree with Mr. Wise and Mr. Newman in their comments on the increased sensitivity to notches or defects of high-strength parent material or weld metal. However, I believe we still have good reason to look into the question of the geometry of weldments in high-strength steels, to see if there are ways of taking advantage of their better tensile properties. It has often been shown that the intrinsic fatigue strength of a steel is related to its tensile strength. When, however, high-strength steels are welded or riveted, we find little advantage in fatigue properties over mild steel. The behaviour of the riveted joint has been extensively studied at the North-Western University in the United States, where mild steel and a large range of alloy steels were tested. In the riveted form all the steels gave an S/N result that could be encompassed in a narrow scatter band showing rather low fatigue resistance. Again then, there is no advantage in using high-strength steels when one has the stress-concentration effect of the rivet hole with the increased stress-concentration due to rivet bearing. When, however, the same shear connections were made with high-strength bolts, the fatigue curves were separated one from another and the high-strength materials began to show a better relative performance. This result does indicate that we might yet be able to do something by way of improving joint geometry and reducing stress concentration effects so as to gain better fatigue properties for welded joints in high-strength steels.

When we compare fatigue results with those of mild steel we must, of course, take some care in interpretation, since the mild steel control values can be widely variable. The evaluation of any data for high-strength steels should, therefore, be done carefully if we are to appreciate what the real increases or decreases of strength might be.

Dr. J. S. Blair: There are, of course, occasions when the use of high-tensile steel is fully justified because fatigue failure is not always the design criterion, and the saving in weight of steel that can be obtained with high-tensile materials is often of some importance. In regard to fatigue conditions, however, I am mystified by the Stallmeyer and Munse paper, and what Mr. Newman has said does not clarify the situation. To start with, the paper states that there is an increase of fatigue strength with increasing tensile strength—indeed it appears to be strictly proportional—and yet the conclusions state that there is no effect. One of the conclusions is, for example, "... the fatigue strength on a zero-to-tension stress cycle of transverse butt welded joints in low-alloy structural steels does not differ significantly from the strength of the same type of joint in ordinary mild grade structural steel when the comparison is made at 2×10^6 cycles." Thus the introductory statement and this conclusion seem to be quite contradictory. The data in Fig. 2 appear to support the first statement, but it is difficult to see why the relationship should be given as precisely as 0·512, suggesting an accuracy of one part in five hundred, when the scatter of results is large. Broadly, however, it is suggested that tensile-strength/3 gives the 2×10^6 cycles stress, and tensile-strength/2 the 10^5 cycle stress, so that strict proportionality would appear to be claimed.

There is another feature of Fig. 2 that is not clear. A number of points are plotted at 64,000 lb/sq.in. whereas Table II shows the tensile strength of mild steel to be 61,000 lb/sq.in.

Professor W. H. Munse: The table gives the average value of the type of material concerned, and Fig. 2 the actual strengths of the material that was tested.

Dr. J. S. Blair: From Fig. 2 it seems then that there is some evidence of increasing fatigue strength if one ignores the highest strength steel. Figure 3 is also somewhat mystifying. In his introduction Professor Munse said that since the two lines in the Goodman diagram were parallel, high-tensile steel showed less advantage under full reversal of stress. In fact, scaling off these diagrams, there seems to be no substantial difference between the alternating and zero-to-tension cycles. Furthermore, the static strengths indicated are well below those quoted in the tables for both mild and low-alloy steels.

We know, of course, that the T.1 steel is strongly advocated for bridge and structural work, but when fatigue is concerned it appears, from Professor Munse's results, that in fact this material may be no better than mild steel. As I have said, all this is mystifying and I might say that the situation is made no better by Mr. Newman's diagram. If one considers the results on this diagram for as-welded joints in higher-tensile steels, then fatigue strength *increases* with *decreasing* tensile strength—one might ask if the materials were perhaps tested in the order shown! On the other hand, black plate properties remain sensibly constant. One has the state of affairs then that for welded joints (and neglecting the high fatigue values for T.1 steel in Fig. 2 of the paper) the line for 2×10^6 cycles might almost be drawn the other way, and this would then confirm Mr. Newman's results! This might be possible although not very logical. Thus we have a complete conflict of results and we can only assume that in using high-tensile steels there is nothing to be gained and perhaps something to be lost.

Professor W. H. Munse: If one looks at the mild steel results in Fig. 2 it will be seen that there are several points in the tensile strength range 58,000–64,000 lb/sq.in. And even here there is a notable variation in the fatigue strength of transverse butt welds. An average value was taken for drawing the straight line and it passes reasonably well through the results for A-242 steel. The silicon steel (81,000–84,000 lb/sq.in. tensile strength) falls below the line, and one could almost draw a vertical line here connecting with the lower results for T.1 steel. What we have to bear in mind, however, is that there are several factors, other than steel type, which have not been accounted for in this figure; undoubtedly variation in joint geometry is one of them. The T.1 test pieces were in ½ in. plate and the

others in thicknesses of $\frac{3}{4}$, $\frac{7}{8}$ and 1 in.; different types of electrode were also involved, and not all of the test pieces were made in the laboratory. Perhaps it is not surprising that there are difficulties of interpretation.

I would agree with Dr. Blair about the accuracy of the straight line relationships. In my introduction of the paper I referred to values of 0·5 and 0·35 for 10^5 and 2×10^6 cycles respectively.

Dr. R. Weck: I would like to draw attention to what is said in the paper concerning fillet welds. In the double-T joint that has been tested there is certainly a notch effect at the root, initiating failure through the throat of the fillets. The fatigue strengths quoted are based on the total throat area and it is stated that the strength of a joint of this type is dependent upon the strength properties and area of the deposited weld metal. This is something which, I think needs more adequate proof because what is said, in effect, is that if one doubles throat area one automatically doubles the load-carrying capacity of the joint; and I do not feel that we can accept this as being true. Many years ago, Professor Wilson at Illinois University showed that, if a certain minimum size of fillet was established, the fatigue strength of a welded joint was not otherwise dependent on fillet weld size. It seems basically wrong then to consider fatigue strength in terms of stress on the throat. This is alright for static loading where, conventionally, stress on the throat is taken to determine weld size, but for fatigue loading conditions one should consider stress in the plate and so double the plate area, not the throat area, if one wants to double the load-carrying capacity. I feel there is a danger of being misled on this point by the paper.

Professor W. H. Munse: Very little work has been done on the variation of weld size in these particular specimens in high-strength steel and it is, perhaps, incorrect to imply that one could generally extrapolate the results in terms of weld area. I would, however, like to check this matter further.

Mr. R. P. Newman: I am sorry to have added what appears to be confusion to an already complicated subject. However, the test data I used in the diagram for 'as-welded' joints emanated from several sources, and it is not really surprising that there are variations of strength. It is, I think, simply fortuitous that they fell out in continuous order in such a way that might indicate that fatigue strength would ascend if tensile strength descended. It was for this reason that we set up as a marker the range of results that we knew had been reported for mild steel, so as better to interpret the variations in the high-tensile steel results. Personally I find it of more interest to consider the apparent consistency of the black plate because here, presumably, we are not concerned with notches of any severity and one might have thought that tensile properties would have had a fair chance to operate, which they did not. Here, I suggest is one area for immediate examination by metallurgists, namely, the study of black plate properties. It is, at least, a proposition that is not much bound up with the complexities that engineers will insist on bringing in to confuse this subject.

Dr. J. S. Blair: I am not confused, I am merely mystified. It is quite clear to me what these tests show; the only thing is they are completely contradictory. If, on the basis of the first four or five results on his diagram, Mr. Newman had proposed to correlate fatigue and tensile strength, he would have had to show just the opposite relationship to that put forward in the paper.

Mr. D. C. C. Dixon (Cleveland Bridge & Engineering Co. Ltd.): I would suggest that the wide variations of strength we have been hearing about come largely from the materials supplied by the mills. Within the Standard for mild steel, BS.15, one can get a steel with such a combination of carbon, silicon, and manganese that it cannot be welded; we have had some. In doing one individual job it is possible to get such a variation of composition from cast to cast that welding procedure has to be altered. It is indicated at the end of the paper that we should fabricate a little better and more consistently, but when materials vary so much I fail to see how we can weld consistently using the same method.

At the end of the paper there is a reference to weld defects, and I should like to know if Professor Munse can attribute loss of strength to any particular types of defects. As fabricators we do not like to be told to make any welded article perfect; we do like to be told that we must avoid certain defects, and we would like that guidance.

In fabricating works today considerable precautions are taken to obtain good welds, for fatigue conditions among other things, and after this morning's discussion I am quite unsure as to whether we are justified in taking any such trouble. As an example, in the construction of plate girders we shot blast the centre of the flanges and the edges of the web plate to get rid of impurities. We also calibrate the speed of travel of automatic welding machines to make sure they are right, which seems more than is done for the fatigue testing machines! We not only check the welding current, but make sure that it remains consistent. I would ask, as the man who has to make it, for some guidance on what exactly we must provide in the way of quality.

Professor W. H. Munse: With reference to defects, I believe that the work being done at B.W.R.A. on the influence of defects should add a great deal of information to the problem mentioned. Variation of steel composition is also a problem we have. Just how all these questions can be answered now is a matter of some difficulty, but I am happy that the discussion has indicated to research workers that there are many important matters to consider and that it should be very easy to get support for future research!

Dr. A. Nicholson: I would like to hear some comments on the influence of composition. In a recent lecture, Mr. Wilkinson of Bristol Aerojet showed that the effect of sulphur, not only in the weld metal but also in the parent metal, can be important. Tests on SAE4130 steel (0·3% C, Ni, Cr, Mo) suggested a correlation between the sulphur content of the plate and fatigue life; sulphur content could also be linked with the incidence of hot-cracking. With low-sulphur plate, careful welding procedure and heat-treatment, the fatigue performance of a welded joint was markedly improved.

Mr. T. R. Gurney (B.W.R.A.): The slope of the 2×10^6 cycle curve shown in Fig. 2 appears to be rather optimistic. In fact the scatter seems to be remarkably small and one could quite well draw a vertical line at about 23,000 lb/sq.in. and produce a scatter band of about $\pm$2000 lb/sq.in. Such a variation could quite easily be accounted for by reinforcement shape and nothing else. Perhaps the main difficulty here is that investigators have tested transverse butt welds to try and sort out materials. If the tests had been done with fillet welded specimens there would probably have been less confusion, particularly if the longitudinal, non-load-carrying weld had been used. Such a specimen is known to give very much less scatter and seems eminently more suitable for studying the influence of materials.

Referring back to the double-T fillet welded joint, the results of tests on mild steel, which should be relevant, show that strength increases with increasing size of weld up to the point where failure shifts from the throat to the

toe of the weld, that is, where plate failure occurs rather than weld failure. I believe that Professor Wilson's tests did actually give this result.

Mr. J. E. Russell: I would like to make one or two random observations arising out of the discussion and the Chairman's challenge to metallurgists. There are two matters to keep in mind in connection with this subject. One is that, however much one might play around with the metallurgy of steel, one cannot really avoid the fact that steel will normally show a fatigue strength equivalent to about one half its tensile strength. Some work now proceeding at B.I.S.R.A. is concerned with this aspect and may well throw some light on the generally consistent fatigue behaviour of steel, and perhaps on the reason for the reduced performance of steels above about 80 tons/sq.in. tensile strength. The second point is that, although the steelmaker might well succeed in producing materials with optimum properties and structure, welding can only bring about a modification in the heat-affected zone which the steelmaker can do nothing about.

There are two questions in connection with the paper itself. Firstly, for the very high-tensile material, was it possible to correlate the range of fatigue strengths with the mode of failure, assuming that failure occurred either through the weld metal or at the edge of the reinforcement? Secondly, were the materials examined to see whether grain size could be correlated with the results, since we know that in other kinds of test the influence of grain size can be quite important?

Finally, I think it is possible we may be over-emphasizing the influence of defects. One or two inclusions in a clean weld could possibly be more damaging than a lot. In rotating bending tests, for example, it has been observed that a complete screw thread can have better fatigue properties than a specimen with a single notch of the same form as the thread. Arguing from this it might be said that one should put in a lot of stress concentrations if one cannot get rid of them altogether!

Professor W. H. Munse: In reply to Dr. Nicholson and Mr. Russell, we have primarily been concerned with deriving strength data for inclusion in specifications, and have not yet had time to look into such matters as the influence of composition and grain size. In regard to the T.1 results, I think I am right in saying that specimens at the higher end of the strength range failed at the edge of the weld (and these presumably had the best geometry) and those at the lower end failed through the weld.

It will have been noted that Mr. Newman, Mr. Gurney, and I have looked at the same data and have produced different interpretations of them. Dr. Blair has also put his interpretation upon the results. Perhaps it would be useful if a study of the problem of the interpretation of fatigue data was made.

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BOOK REVIEW

IIW: "*List of Terms Used in Ultrasonic Testing*", 1959, International Institute of Welding, Paris.

The purpose of this booklet is given in the introduction: "The Commission on Testing, Measurement and Control of Welds of the International Institute of Welding has pleasure in presenting in a booklet in three languages a collection of the terms used in ultrasonic testing. "The terms adopted are those established by common use in each country . . ."

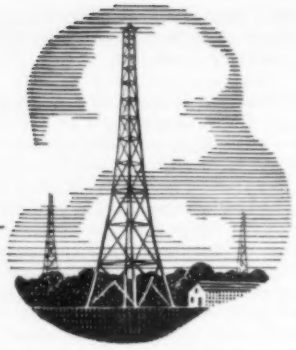
"The dictionary is composed of: (1) A methodical multilingual classification of terms in a logical order. Each of the terms is given a number which is the same whatever language. The list is subdivided into sections to make it easier to find a term. It also contains some pages of drawings in which the terms, whose number is followed by an asterisk, are illustrated . . ."

In a new and rapidly developing branch of non-destructive testing it is important for different countries to become aware quickly of what is going on in other countries, and this booklet can assist in this way.

To estimate some measure of the completeness of coverage of the system, 24 terms were chosen at random from three different articles in the literature of ultrasonic flaw detection. Of these, it was found that 13 were included in the booklet; of those not included 8 related to defects which are commonly found by ultrasonics, one was the word "diffraction" and another "length scan". A closer examination of the dictionary showed very little mention of the different defects which are the main reason for resorting to non-destructive testing. If these are already collected in some other dictionary, then it would appear to be desirable to refer to that dictionary or, better yet, to repeat them here for the convenience of serious users of the dictionary. A few minutes spent in running though the terms revealed a number of other gaps; *e.g.*, the only sort of medium mentioned is a dispersive medium—there is nothing about double refraction of anisotropy. There were time-bases, which were "delayed", "expanded" and "contracted", but no "linear time base". There were several terms relating to transducers, but the word "piezo electric" was not mentioned, nor were the piezo-electric constants referred to. "Beams" and "beam axes" and the "directivity function" were mentioned, but nothing about "side lobes" and nothing about the "near zone" or "far zone", although "far field" is mentioned in the notes, but not in the dictionary proper. The other principal omission that strikes the reviewer is that no definitions are given, except those implicit in the "pages of drawings".

D. O. Sproule

NEWS
and Announcements



News of the Institute and Branches
B.W.R.A. · Other Societies ·
and Industry

INSTITUTE ACTIVITIES

Annual General Meeting, 1960

The Annual General Meeting of the Institute will be held at 54 Princes Gate, London, on Thursday 14th July, at 2.30 p.m.

Spring Meeting 1961

The Spring Meeting of 1961 will be held in London during the Engineering, Marine, Welding, and Nuclear Energy Exhibition, from 25th to 28th April next.

The theme of the meeting will be recent developments in the welding and allied processes, and invitations are being sent to manufacturers inviting offers of papers on recent developments in welding and brazing and in the welding of plastics. Examples of subjects on which papers will be welcome are: Developments in stud welding; automatic sampling of test pieces in spot welding; developments in manual semi-automatic submerged-arc welding; developments in automatic inert-gas welding; and such developments in brazing as honeycomb and similar constructions.

Appeal to Industry

In response to the appeal, The Tank and Industrial Plant Association has promised an annual subscription of £100 per year.

The Council of the Institute offers its warm thanks to the Association for this addition to the support given on many previous occasions to the work of the Institute.

Conference of Branch Secretaries

On 26th May last the honorary secretaries of some 14 Branches met for a day's conference at the Institute, thus reviving a function which was discontinued in 1956 but used to be an annual event in the Institute's programme. The Secretary of the Institute took the chair and a useful exchange of opinions and experience about a number of matters of importance to the Branches took place. The morning session dealt with the administrative relations between Branches and Headquarters and was opened by Mr. P. D. Boyd, Assistant Secretary.

In the afternoon the Chairman started a discussion on the means of increasing attendance at Branch technical meetings, after which Mr. C. R. Harman, Executive Editor, opened the final debate on the supply of branch news and local news for the *Journal*.

It was the first visit of some of the Branch secretaries to the new Headquarters and the opinion seemed to be that the meeting had been useful, particularly to newly installed secretaries, and should if possible become an annual event again.

Staff

At the end of May, Miss W. R. Urwin left the Institute to take up an appointment in the library of the Institute of Advanced Legal Studies of the University of London. At the time of writing no successor to Miss Urwin had been appointed in the Library of the Institute.

On 10th June, Mrs. Wopling resigned her appointment as secretary to the Secretary of the Institute, and was succeeded by Mrs. Felton. Mrs. Felton acted as temporary secretary during Mrs Wopling's extended period of sick leave at the turn of the year.

Closing of Library

The Institute's Library will be closed throughout the month of August. Queries and applications for loans received during that period will not be answered until the first week of September.

NEWS OF MEMBERS

Mr. M. Birkhead is leaving Messrs. W. P. Butterfield to become Chief Metallurgist at Messrs. Mather & Platt, Manchester.

Mr. A. R. Heaton has joined Mechans Ltd. to undertake development work in connection with special projects.

Mr. G. B. Blackhurst has left the Sales Technical Service Dept. of British Oxygen Gases Ltd., and has joined the Rowenarc Division of the Rubery Owen Group as a Special Applications Engineer.

CONTRIBUTORS TO THE JOURNAL

N. F. Eaton, B.Sc., Ph.D., A.I.M., graduated with honours in Metallurgy at Swansea University in 1952 and obtained the degree of Ph.D. in 1955. Since then he has been employed by the Research Department of Metropolitan Vickers Electrical Co. Ltd., serving them on attachment at A.E.R.E. Harwell from 1956–1958, and at A.W.R.E. Aldermaston from 1958–1960.

T. J. McDonald, B.Sc., A.I.M., Technical Officer with I.C.I. Metals Division, was educated at King Edward's Grammar School, Aston, and at

N. F. Eaton

T. J. McDonald

D. B. Wright

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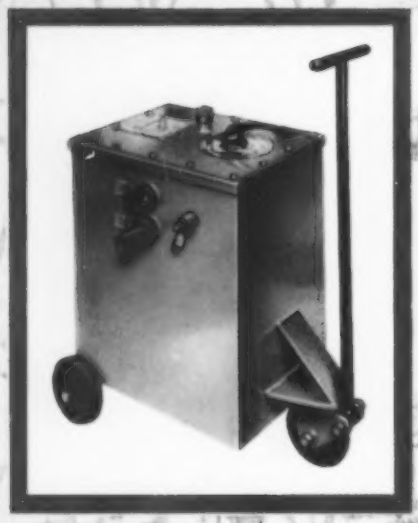

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Current range 30–200 amp.

LWC300
Single-operator set providing an output of 34–315 amp.
This set is also available with a universal winding suitable for 200–275 and 380–550 volts supply.

A.C. will cover the majority of manual arc-welding applications and the LWC range of portable equipment has outputs to handle all work requiring from 16 SWG to $\frac{3}{8}$" diameter electrodes.
They are suitable for a 380/440 volts supply and all have provision for inbuilt power factor correction capacitors ensuring that correction is always available. They are completely oil immersed giving very efficient cooling and reduce maintenance to an absolute minimum.

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A double-operator set providing 315 amp for each of two operators or when heavy welding is required 630 amp for one operator.

LWC600
A single-operator set providing an output of 116–625 amp.

Current rang

LWD350
This rectifie
developed
ern fabric
where D.C
required.
cooled equ
provides a
variable ou
current ran
amp.

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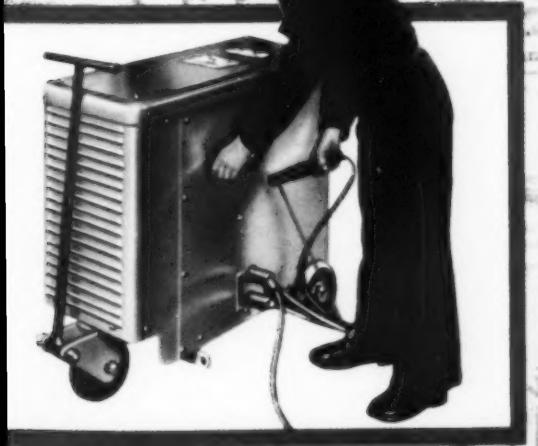
Current range A.C. 34–315 amp.
D.C. 27–250 amp.

LWAD600
Current range A.C. 116–625 amp.
D.C. 95–520 amp.

LWAD450
rent range A.C. 59–450 amp.
D.C. 47–360 amp.

D350
s rectifier set has been eloped to meet mod- fabrication needs re D.C. welding is uired. It is an air- led equipment and vides an infinitely able output over the ent range of 25–350

D.C. EQUIPMENT



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British Standard Wire Gauge		Nearest Fractional Sizes		Nearest Metric Sizes	
SWG	in.	in.	in.	mm.	in.
000	·372	⅜	·375	9·5	·374
0	·324	5/16	·3125	8·0	·315
2	·276	9/32	·281	7·0	·276
3	·252	¼	·250	6·5	·256
4	·232	15/64	·234	6·0	·236
6	·192	3/16	·187	5·0	·197
8	·160	5/32	·156	4·0	·157
10	·128	⅛	·125	3·25	·128
12	·104	3/32	·094	2·5	·098
14	·080	5/64	·078	2·0	·079
16	·064	1/16	·062	1·5	·059
18	·048	3/64	·047	1·25	·049
20	·036	1/32	·031	1·0	·039

TEMPERATURE CONVERSION

°C	°F
0	32
50	122
100	212
150	302
200	392
300	572
400	752
500	932
600	1112
700	1292
800	1472
900	1652
1000	1832
1100	2012
1200	2192
1300	2372
1400	2552
1500	2732

°F	°C
0	−18
50	10
100	38
150	66
200	93
300	149
400	204
500	260
600	316
700	371
800	427
900	482
1000	538
1100	593
1200	649
1300	704
1400	760
1500	816

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IDEAL FOR A WIDE VARIETY OF WORK

This outstanding range of equipments provides a choice of A.C. or D.C. welding current at the turn of a switch. They employ high efficiency oil-cooled silicon diodes requiring virtually no maintenance and are suitable for indoor or outdoor use. The running costs are very low and these versatile sets will cover all manual welding applications.

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D.C. 47–360 amp.

LWD350
This rectifier set has been developed to meet modern fabrication needs where D.C. welding is required. It is an air-cooled equipment and provides an infinitely variable output over the current range of 25–350 amp.

D.C. EQUIPMENT

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SWG	*in.*	*in.*	*in.*	*mm.*	*in.*
000	·372	3/8	·375	9·5	·374
0	·324	5/16	·3125	8·0	·315
2	·276	9/32	·281	7·0	·276
3	·252	1/4	·250	6·5	·256
4	·232	15/64	·234	6·0	·236
6	·192	3/16	·187	5·0	·197
8	·160	5/32	·156	4·0	·157
10	·128	1/8	·125	3·25	·128
12	·104	3/32	·094	2·5	·098
14	·080	5/64	·078	2·0	·079
16	·064	1/16	·062	1·5	·059
18	·048	3/64	·047	1·25	·049
20	·036	1/32	·031	1·0	·039

TEMPERATURE CONVERSION

°C	°F
0	32
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150	302
200	392
300	572
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500	932
600	1112
700	1292
800	1472
900	1652
1000	1832
1100	2012
1200	2192
1300	2372
1400	2552
1500	2732

°F	°C
0	−18
50	10
100	38
150	66
200	93
300	149
400	204
500	260
600	316
700	371
800	427
900	482
1000	538
1100	593
1200	649
1300	704
1400	760
1500	816

HARDNESS COMPARISON TABLE

Brinell No.	*Vickers Pyramid No.*	*Rockwell 'C' No.*	*Shore Scleroscope No.*
627	765	60	84
601	717	58	81
578	675	57	78
555	633	55	75
534	598	53	72
514	567	52	70
495	540	50	67
477	515	49	65
461	494	47	63
444	472	46	61
429	454	45	59
415	437	44	57
401	420	42	55
388	404	41	54
375	389	40	52
363	375	38	51
352	363	37	49
341	350	36	48
331	339	35	46
321	327	34	45
311	316	33	44
302	305	32	43
293	296	31	42
285	287	30	40
277	279	29	39
269	270	28	38
262	263	26	37
255	256	25	37
248	248	24	36
235	235	22	34

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Where three or more operators are required multi-operator welding equipment comes into its own, having numerous advantages over single operator sets - only one installation for up to 12 points, great saving of floor space, no high voltage trailing cables, more even mains loading and simplified current return system.
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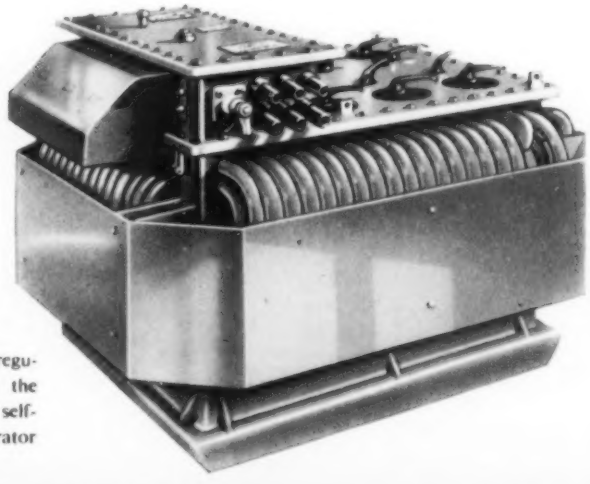
This range consists of standard multi-operator transformers fitted in a tank which has a dry compartment with locking doors, containing the primary fuse switch and power factor correction capacitors resulting in a very safe, compact and weatherproof unit. They are available in four standard sizes of 3, 6, 9 or 12 operators.

LWR

Welding regulators for use in conjunction with multi-operator transformers are available in 210, 350, 450 and 600 amp sizes.
Where very long welding leads are in use, "Shipyard" models are available which ensure that correct welding currents are always obtained.

LWM

Standard multi-operator transformer, available in four standard sizes of 3, 6, 9 or 12 operators.



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Transformer and regulators mounted in the same tank making a self-contained multi-operator welding unit.

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General purpose electrode for welding in all positions.

Standard sizes 16 SWG to ¼"

WELDEES

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For fast and easy welding of mild steel in all positions.

Standard sizes 16 SWG to $\frac{5}{32}$"

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British E.357 American E.6013

All-position electrode expressly designed for vertical and overhead welding.

Standard sizes 12 SWG to ¼"

VOHEES ⚓ 🔔 ⊗

British E.317 American E.7013

An all-position electrode designed for inclined, vertical, and overhead welding.

Standard sizes 16 SWG to ¼"

SPEEDEES 🔔 ⊗

British E.926 American E.6024

Iron powder coated electrode for extremely fast welding in the downhand and standing fillet position.

Standard sizes 14 SWG to ¼"

PRESSUREES 🔔 ⊗

British E.426 American E.6020-6030

Eminently suitable for welding in deep grooves.

Standard sizes 10 SWG to $\frac{5}{32}$"

PRESSUREES IP.1 🔔 ⊗

British E.926 American E.6020-6030 (iron powder)

An iron powder version of PRESSUREES electrode giving extremely fast welding in deep grooves and tight fillets.

Standard sizes 10 SWG to $\frac{5}{32}$"

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For deep penetration welding in downhand and horizontal fillet positions.

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A low hydrogen electrode for welding heavy sections and restrained joints in mild, medium high tensile, carbon and alloy steels.

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HERMEES ⚓ 🔔 ⊗

British E.926 American E.7016 (iron powder)

A low hydrogen electrode with an iron powder coating for the very fast welding of heavy sections and restrained joints.

Standard sizes 12 SWG to $\frac{5}{32}$"

HERCULEES 35 ⚓ 🔔 ⊗

British E.916 American E.7016

A low hydrogen electrode for all position welding of mild, medium high tensile, carbon and alloy steels.

Standard sizes 10 SWG to ¼"

FILLEREES

British E.925

An electrode primarily designed for filling holes or cavities in steel castings, producing little or no slag.

Standard sizes 10 SWG to $\frac{5}{32}$"

STAINEES M

An austenitic 18/8 chromium/nickel stainless steel electrode giving a deposit containing approximately 3¼% molybdenum.

Standard sizes 16 SWG to 4 SWG

STAINEES N

An austenitic 18/8 chromium/nickel stainless steel electrode stabilised with niobium to prevent weld decay.

Standard sizes 16 SWG to 4 SWG

STAINEES MN

A stabilised austenitic 18/8 chromium/nickel stainless steel electrode giving a deposit containing approximately 2·75% molybdenum.

Standard sizes 8 SWG to 4 SWG

PYRISTEES 1

British E.317M

An all-position electrode for welding creep resisting steels working under a service temperature up to 950°F.

Standard sizes 10 SWG to 4 SWG

PYRISTEES 2

An all-position electrode for welding creep resisting steels working under a service temperature up to 1050°F.

Standard sizes 10 SWG to 4 SWG

HARDEES 250

For producing machinable deposit with high resistance to abrasion. Hardness of deposit 240–280 V.P.H.

Standard sizes 12 SWG to 4 SWG

HARDEES 350

For producing a deposit which has high resistance to abrasion and impact. Hardness of deposit 350–400 V.P.H.

Standard sizes 12 SWG to 4 SWG

HARDEES 650

Producing an extremely hard abrasion resistance deposit. Hardness of deposit 650–700 V.P.H.

Standard sizes 12 SWG to 4 SWG

MANGANEES

For building up 12–14% manganese steel.

Standard sizes 10 SWG to 4 SWG

CASTEES N

An all-position electrode for welding grey cast iron giving a readily machinable deposit without pre-heating.

Standard sizes 12, 10 and 8 SWG

CASTEES SG

Particularly developed for welding spheroidal graphite and high duty cast irons.

Standard sizes 12, 10 and 8 SWG

GROOVEES

For the grooving, gouging and piercing of all metals including cast iron and stainless steels without additional equipment.

Standard sizes 10 SWG and 8 SWG

Key to symbols : ⚓ **Admiralty approved** 🔔 **Lloyds Register of Shipping approved** ⊗ **Ministry of Transport approved**

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...WITH THIS GREA

Tear out for easy reference

here three or more operators are required
ulti-operator welding equipment comes into
own, having numerous advantages over
gle operator sets—only one installation for
to 12 points, great saving of floor space, no
gh voltage trailing cables, more even mains
ading and simplified current return system.
e transformers, for use in conjunction with
ndard regulators, are manufactured in four
ndard sizes for 3, 6, 9 or 12 operators at
0 amp each and are suitable for operation
om a 3 phase 50 cycles supply. They are
remely robustly constructed and suitable for
door or outdoor operation.

LWMC

his range consists of standard multi-operator trans-
ormers fitted in a tank which has a dry compartment
ith locking doors, containing the primary fuse switch
nd power factor correction capacitors resulting in a
ery safe, compact and weatherproof unit. They are
vailable in four standard sizes of 3, 6, 9 or 12 operators.

R

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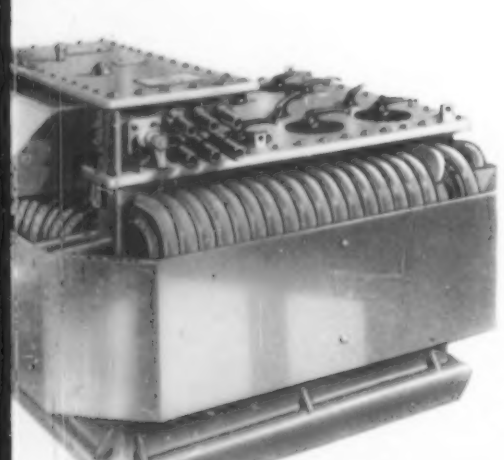
ailable which ensure that
re always obtained.



'ENGLISH ELECTRIC'

ELECTRODES

ENROX

British E.217 American E.6012

General purpose electrode for welding in all positions.

Standard sizes 16 SWG to ¼"

WELDEES

British E.217 American E.6012

For fast and easy welding of mild steel in all positions.

Standard sizes 16 SWG to 5/16"

VERTEES

British E.357 American E.6013

All-position electrode expressly designed for vertical and overhead welding.

Standard sizes 12 SWG to ¼"

VOHEES

British E.317 American E.7013

An all-position electrode designed for inclined, vertical, and overhead welding.

Standard sizes 16 SWG to ¼"

SPEEDEES

British E.926 American E.6024

Iron powder coated electrode for extremely fast welding in the downhand and standing fillet position.

Standard sizes 14 SWG to ¼"

PRESSUREES

British E.426 American E.6020-6030

Eminently suitable for welding in deep grooves.

Standard sizes 10 SWG to 5/16"

PRESSUREES IP.1

British E.926 American E.6020-6030 (iron powder)

An iron powder version of PRESSUREES electrode giving extremely fast welding in deep grooves and tight fillets.

Standard sizes 10 SWG to 5/16"

DEEPEES

British E.125P American E.6011

For deep penetration welding in downhand and horizontal fillet positions.

Standard sizes 10 SWG to 5/16"

LOWHEES

British E.616 American E.7016

A low hydrogen electrode for welding heavy sections and restrained joints in mild, medium high tensile, carbon and alloy steels.

Standard sizes 14 SWG to 5/16"

HERMEES

British E.926 American E.7016 (iron powder)

A low hydrogen electrode with an iron powder coating for the very fast welding of heavy sections and restrained joints.

Standard sizes 12 SWG to 5/16"

HERCULEES 35

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Standard sizes 10 SWG and 8 SWG

Key to symbols: ⚓ Admiralty approved Lloyds Register of Shipping approved ⊗ Ministry of Transport ap

ENGLISH ELECTRIC

set the pace

...WITH THIS GREAT RANGE OF

WELDING EQUIPMENT

ELECTRODES & ACCESSORIES

Tear out for easy reference

'ENGLISH ELECTRIC'

NEW THERMEES

ELECTRODES

FOR

PRE-HEATING

An electrode designed for applying concentrated heat in the right place with maximum ease.
Can be operated from both A.C. and D.C. welding equipment and requires no additional equipment.
Applications include pre-heating, post-heating, straightening buckled plates and numerous other jobs where easy heating of metals is required.
Manufactured in 6, 8 and 10 swg sizes.

USEFUL TABLES

COMPARATIVE ELECTRODE SIZES

British Standard Wire Gauge		Nearest Fractional Sizes		Nearest Metric Sizes	
SWG	in.	in.	in.	mm.	in.
000	·372	⅜	·375	9·5	·374
0	·324	5/16	·3125	8·0	·315
2	·276	9/32	·281	7·0	·276
3	·252	¼	·250	6·5	·256
4	·232	15/64	·234	6·0	·236
6	·192	3/16	·187	5·0	·197
8	·160	5/32	·156	4·0	·157
10	·128	⅛	·125	3·25	·128
12	·104	7/64	·094	2·5	·098
14	·080	5/64	·078	2·0	·079
16	·064	1/16	·062	1·5	·059
18	·048	3/64	·047	1·25	·049
20	·036	1/32	·031	1·0	·039

TEMPERATURE CONVERSION

°C	°F
0	32
50	122
100	212
150	302
200	392
300	572
400	752
500	932
600	1112
700	1292
800	1472
900	1652
1000	1832
1100	2012
1200	2192
1300	2372
1400	2552
1500	2732

°F	°C
0	−18
50	10
100	38
150	66
200	93
300	149
400	204
500	260
600	316
700	371
800	427
900	482
1000	538
1100	593
1200	649
1300	704
1400	760
1500	816

HARDNESS COMPARISON TABLE

Brinell No.	Vickers Pyramid No.	Rockwell 'C' No.	Shore Scleroscope No.
627	765	60	84
601	717	58	81
578	675	57	78
555	633	55	75
534	598	53	72
514	567	52	70
495	540	50	67
477	515	49	65
461	494	47	63
444	472	46	61
429	454	45	59
415	437	44	57
401	420	42	55
388	404	41	54
375	389	40	52
363	375	38	51
352	363	37	49
341	350	36	48
331	339	35	46
321	327	34	45
311	316	33	44
302	305	32	43
293	296	31	42
285	287	30	40
277	279	29	39
269	270	28	38
262	263	26	37
255	256	25	37
248	248	24	36
235	235	22	34

the College of Technology, Birmingham. He obtained the London University degree in Metallurgy in 1956.

Before secondment to the Atomic Weapons Research Establishment in 1957, he was engaged in the Metals Division Research Department on problems associated with the joining of the Company's non-ferrous products. In 1958, he was transferred to the newly-formed Beryllium Project at Witton, which is producing beryllium components for the U.K.A.E.A. Advanced Gas-Cooled Reactor experiment.

D. B. Wright, B.Sc., who is at the Atomic Weapons Research Establishment, Aldermaston, received his technical education at Birmingham University, where he obtained an honours degree in Physical Metallurgy in 1950. During the following three years, he was engaged on research work on strain ageing as applied to fatigue, at Birmingham, and subsequently joined the A.W.R.E. in 1953, where his work mainly entails research on beryllium.

A. G. Brain, A.I.M., Research Officer in the Welding Processes Section of the British Welding Research Association, was educated at Kingswood Grammar School, Bristol, and at Cambridge University, where he graduated in 1947.

Following a period in the telecommunications industry he joined the then Bristol Aeroplane Company in 1949, and was employed successively in the aircraft and engine divisions on welding and foundry metallurgy. He took up his present appointment in 1952 and has been concerned with an evaluation of the CO_2 process and also with the welding of zirconium.

Mr. Brain became an L.I.M. in 1954 and obtained the A.I.M. by examination in 1958.

BRANCH NEWS

East of Scotland — A.G.M.

On Wednesday, 13th April, the Branch helds its Annual General Meeting which was very well attended.

After the formal business there was a display of the following films:

"*Birth of a Tanker*" (Petroleum Films Bureau)

"*Engineering at Calder Hall*" (Ace Distributors)

"*Welding Gantry*" and "*The Twin Fillet Welder*" (Quasi-Arc Ltd.)

The Branch is indebted to the suppliers of these films, which are of great interest and can be recommended for showing to any audience interested in modern fabricating techniques.

R.D.B.

North London — Slough Section

On Tuesday, 5th April, Mr. R. B. Whalley was the lecturer for the evening at the Section meeting held at the Community Centre, Slough, when he chose as his subject "*Shop Inspection of Welds*".

Mr. Whalley dealt with the various points that affect good welding: design, procedure, workshop practice, and the various precautions and controls necessary to produce good and consistent work. Various methods of testing, such as ultrasonic, radiographic with both X-ray and gamma-ray techniques, crack detection, dye penetrants, fluorescent inks, and leak detection, were covered, and an interesting question time ensued when many different problems were most ably dealt with and assistance given. Mr. Brookbank, newly elected to the Slough Committee, proposed the vote of thanks and remarked on the many branches of the inspection field mentioned in the lecture, and the detailed way they were dealt with, noting that the lecturer found no need for notes or a written paper.

R.B.W.

Liverpool — Lecturers entertained

The 16th Annual Dinner to entertain the session's lecturers was held on 8th April, as usual (but only just!) at the St. George Restaurant, Liverpool. This event is fast becoming so popular that the management were hard pressed (and likewise some of the diners) to accommodate the throng. At the end of an excellent repast the Chairman, Mr. K. J. Ward, proposed the Loyal Toast and introduced the guests, who included, as well as some of the lecturers, the Presidents of the neighbouring Manchester and Preston Branches. Professor Keaton and Professor Owen. In the absence through illness of the Principal Guest, Mr. Gilbert Roberts (Vice-President of the Institute) a brief speech was made by Mr. Colin Spencer. As a stalwart member of the Wolverhampton Branch and an old friend of his hosts of Liverpool, Mr. Spencer was able to give some well-deserved praise to the honorary officers of the Liverpool Branch. He referred particularly to the hard work done by the Secretary, Harry Cox, over many years of loyal service, and by the Treasurer and Past Chairmen.

The remainder of a most enjoyable evening was filled with varying entertainment led by Bill Connerton. In an original calypso the entertainers revealed some interesting facts about the past lecturers and other guests.

Wolverhampton — Welding for Nuclear Power

The subject for the evening at the meeting held on 25th March was "*Fabrication in a Nuclear Power Station*" by Mr. S. H. Griffiths.

Mr. Griffiths opened his paper by giving a few general remarks on the types of stations which are being studied and designed today, and said that in the U.K. the accent, so far, has been on the graphite-moderated gas-cooled pile. The experience gained during construction of the Calder Hall Reactors and earlier plant at Windscale and at Harwell has given the necessary confidence for the C.E.G.B. to choose this type.

The choice of materials used in the fabrication of such large vessels was also discussed and a slide giving an idea of the essential parts which have to be dealt with by the fabricator were shown. These were:

Reactor pressure vessel—50 ft. dia., 80 ft. high, 3 in. thick
Diagrid
Gas ducting
Heat exchangers or boilers.

To ensure that most difficulties are avoided, it is inherent in the choice of steel that it should have good welding characteristics. It must also be borne in mind that these vessels had to be fabricated to Class I standards and *in situ*. One original consideration for the Berkeley station, the possibility of creep was eliminated by gas cooling the shell, and the problems were those of meeting the physical and weldability requirements.

Mr. Griffiths at this point went on to say that later information has revealed that during service the effect of irradiation may embrittle the steel, and on future stations this problem will have to be borne in mind.

The steel for this reactor was in large plate forms of the order of 20 ft. × 10 ft. 3 in, and to ensure good weld- 0·16%. It is known and appreciated that variation over plates of this size may be ability the carbon was restricted to as much as 0·09% so, instead of specifying a top limit for carbon, a more realistic approach was made by specifying the low figure, in the knowledge that some parts of the plate would exceed this amount but would still be low enough to ensure good weldability.

The manganese content was relatively high to ensure maximum notch toughness, and a silicon killed steel was

chosen to ensure optimum creep properties, though aluminium killed steel would give better notch toughness.

Opening his remarks on inspection, Mr. Griffiths stated that the term Class I Pressure Vessel was familiar to most people and this has come to represent a very high standard of workmanship, but the vessels being built at the present time are being built to a standard that can only be described as Class I+. Mr. Griffiths then pointed out that to attain this standard the quality of the parent plate becomes even more important, and to ensure that it is free from such significant defects as lamination, slag stringers, etc., the use of ultrasonic and magnetic examination for welding edges has increased. He then explained by the use of slides some of the appropriate methods used in inspection of these plates.

According to the part of the plant for which they are to be used, the plates will be either pressed or formed. By the use of slides the various methods of forming such as horizontal rolls, vertical rolls, and the universal press, were shown. The crown plates for both reactor vessels and boilers are hot pressed in segments and later assembled to form a crown.

Welding preparations have to be cut on these formed plates and by the use of further slides Mr. Griffiths showed the principle of the 'pendulum' cutter used for preparation of the crown plates. This is a pendulum arm made of Dural tube at the end of which is situated the cutting head, the arm being adjustable to allow smaller radii to be cut. The arm rotates through 360° to allow cuts on four sides to be made at one setting and magnetic system attached to the cutting head allows templates to be used. Slides showed the machines used for the cutting of the control rod and charge tube holes in the top of the dome.

The welding of the job was completed using manual metal-arc welding, with the exception of the heat exchanger sections which were manually welded and pre-fabricated on the longitudinal seams. Double-V preparations were used wherever possible to minimize distortion. All operators had to pass qualification tests in the position they were going to weld.

Mr. Griffiths then illustrated the method of assembly and gave details of the fabrication of the bottom domes at site and the build up of the vessel after the bottom dome had been moved from its original site to allow civil engineering work to proceed and to allow large cranes to lift these smaller plates into position.

Stress relieving of the vessel was carried out with radiant elements by raising the vessel to 600°C. and holding this for several hours by means of outside lagging. 2½ MW of current was made available for this purpose. The boilers were stress relieved locally by means of induction heating.

Pressure testing was done pneumatically to 211 lb/sq.in. with the temperature maintained slightly above ambient, and strain gauges and brittle lacquer were used for observation of highly stressed areas.

The assembly of the heat exchangers was then described, from the assembly of the dome ends to the assembly of the heat exchanger at site. After stress relief, the stub tube welds were examined by magnetic crack detection and the equipment was then transported to its position adjacent to the R.P.V. By the use of a low loader and derricks, it was then lifted vertical and allowed to settle on its base.

Finally, Mr. Griffiths showed a recent slide of the site at Berkeley and one could appreciate the great amount of planning, in regard to the choice of materials, inspection and welding, required to make this work possible.

After a very lively discussion, opened by Mr. L. C. Dipper, the vote of thanks was proposed by Mr. M. R. Liddiatt and seconded by Mr. J. Askin.

J.W.G.

INTERNATIONAL INSTITUTE OF WELDING

Liège Assembly

Four British papers, contributed to the colloquia, were a novel feature of the International Institute of Welding's Annual Assembly at Liège this year. Dr. T. P. Hoar, Mr. W. E. Ballard, and Mr. A. R. Old presented papers in the colloquium on metal spraying, which was held by Commission I, and Dr. Horne contributed to the colloquium on the influence of residual stresses on the stability of welded structures and structural members, held by Commission X.

Meeting in April to review the position of the British Delegation, the Joint Committee for International Welding Relations, which acts for the British member societies of I.I.W., found that well over fifty British delegates, experts, and observers proposed to attend the assembly.

OTHER SOCIETIES

French Metallurgical Society

The Autumn Meeting of the Société Française de Métallurgie is being held in Paris from 17th to 21st October 1960. The theme is to be the "Heat Treatment of Metals and Alloys".

Symposium on fatigue

A symposium on topical problems of fatigue strength, especially of large-size parts will take place on 9th–10th September, 1960, in Prague, under the auspices of the Czechoslovak Scientific-Technical Association.

Papers referring to the following principal groups of topics will be discussed:

(i) Physical aspects of the origin and development of fatigue damage to metals.
(ii) Metallurgical and technological factors affecting fatigue strength, especially in a favourable sense
(iii) Influence of size and shape of parts on fatigue strength and service life
(iv) Influence of stress history on the fatigue strength of parts.

Further information can be obtained from the Secretariat of the Symposium, c/o Československá vědecko-technická společnost, Široká 5, Praha 1—Staré Město, ČSR.

Non-destructive testing

A Conference on the "Theory and practice of ultrasonic inspection" is to be held at the Queens Hotel, Cheltenham, between 22nd and 24th September, 1960. The arrangements are being made jointly by the Institute of Physics' Non-Destructive Testing Group, the Society of Non-Destructive Examination, and the Non-Destructive Testing Society of Great Britain.

Further details of the programme, and of hotel accommodation in Cheltenham, can be obtained from the Conference Secretary, Mr. I. M. Barnes, Materials Laboratory, De Havilland Propellers Ltd., Hatfield, Herts.

Organization of Standards Engineers

At the 6th Conference of Standards Engineers it was decided to invite British Standards Engineers to become associates, on a personal basis, of the British Standards Institution, instead of forming a separate organization. The associates would be organized on a regional basis to provide convenient centres for meetings, and initially a fee of a guinea a year would be charged for B.S.I.'s services.

Standards Engineers wishing to participate in this scheme are invited to write to the Joint Secretary, I. Prod. E./B.S.I. Committee, British Standards House, 2 Park Street, London W.1. An inaugural meeting will be held in London on 8th July.

NEWS FROM INDUSTRY

Aluminium Strip Production

A very considerable increase in production capacity has been made possible by the installation, at the Woodgate Works of Birmetals Ltd., of a new Sendzimir cold reversing mill. The new plant was officially started by the Marquess of Exeter on 7th April.

The mill, which is the first to be operated in Europe for aluminium alloy strip production, can roll 48 in. wide strip in a thickness range from 0·1875 to 0·006 in. at a maximum speed of 1600 ft/min. This remarkable capacity is

possible because of the high precision of the machine, the small work rolls, and full electronic control. A roll change can be made in less than half a minute.

Because of the high operating speed the existing casting and rolling capacity at Birmetals was insufficient to enable large enough coils to be made. The new mill can accept coils up to 10,000 lb whereas the largest coil available from the existing 4-high mill is 8,000 lb. The Company therefore had to consider the alternatives of expanding their hot rolling capacity at a cost of about two million pounds, or of providing means for joining smaller coils.

Flash butt welding is used for this purpose in steel strip mills but it is a most difficult electrical and engineering task to apply the process to wide aluminium strip. The high electrical and heat conductivity of aluminium means that very much higher electrical loads and a greater degree of mechanical control are needed than for the welding of steel strip. It was estimated that for welding the 52 in. wide strip from the hot mill a load of 1330 amp at 400V would be needed, followed by a forging load greater than 4000kVA. This demand, which would be unbalanced, with a very low duty-cycle, was completely unacceptable to the electricity supply authorities, and some means of reducing the peak load had to be devised.

The project for a suitable flash-butt welder was put in the hands of A.I. Electric Welding Machines Ltd., who were responsible for the design and installation of the final welding equipment.

The high speed of the new cold mill meant that any joint in the strip had to be mechanically and metallurgically sound, for any breakage within the mill would be disastrous. In addition, because of the precision and high finish of the work rolls, surface imperfections on the sheet could not be allowed, so that perfect alignment and absence of upset material were essential.

Extensive pilot tests on narrower strip proved that adequate properties could be attained, and the manufacture of the final machine was commenced. Many novel features, including the use of a series of capacitors, were introduced to reduce the electrical load, and a fully automatic system was incorporated in the machine. The electrical load on flashing was reduced to 290 kVA (for about 150c) and on forging (about 7c) to 2320 kVA. The capacity of the welder is 3000 kVA.

The welding line itself comprises a pay-off stand, which takes the 2000 lb coils from the 4-high mill, a feeder leveller, shears, the flash-butt welder, upset dresser, edge trimmer, scrap cropper, and the final coiling unit.

The first small coil, up to 52 in. wide and 0·140 in. thick, is passed through the various units with the welder in the open position, and its tailing end is then cropped by guillotine. The end is then inched back against the gap gauge of the welder and is clamped into position with a load of 250 tons. The second coil is then taken from the pay-off stand, its leading edge is cropped and is again inched into the opposite side of the gap gauge and clamped. The proper edge alignment of the two coils is ensured by air cylinders at the back and front of the machine, controlled by push button.

The gap gauge is then raised and the moving head of the welder is closed up to bring the ends of the coils together. At this point the welding operation is initiated by push button and the flashing and final forging is applied automatically. The edges are sheared at an angle of about 3°, so that the flash is initiated over a relatively small area of material. The total time for welding at 50 in. wide strip 0·14 in. thick is about 10 sec, including the period for initial induction heating.

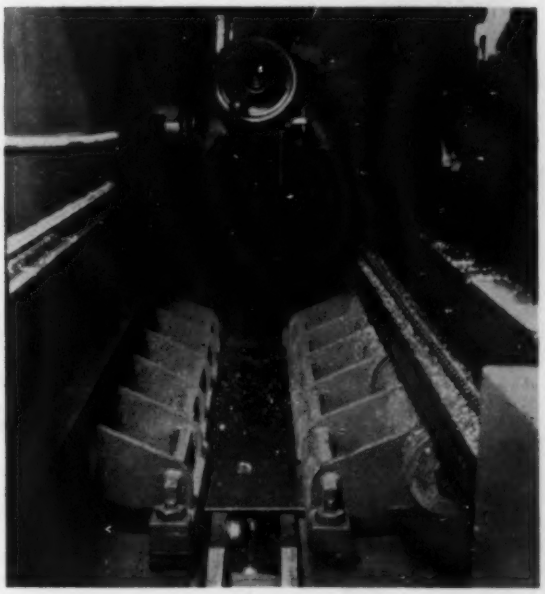
When the weld is complete the joined coil is released from the welder and is moved along so that the weld can be clamped in the Wadkin upset removing unit. This has two routing heads so that upset can be removed simultaneously from the two surfaces to within the thickness limits required. Before passing to the take-up reel the welded strip is edge trimmed to the required width for the Sendzimir mill. The whole operation is repeated as necessary to provide the maximum size of coil needed for the cold mill.

The new Birmetals installation also

The A.I. aluminium strip flash-butt welder installed at Birmetals Ltd.

Cover illustration—*Another view of the A.I. flash-butt welder*

Clamped welded strip on completion of the removal of upset



includes an intermediate coil-annealing furnace with a capacity of 8000 lb/hr, and a flash annealing furnace which will accommodate sheets up to 8 ft wide on a continuous conveyor. The rate of movement through the 40 ft long furnace can be controlled from zero to 100 ft/min.

A slitting line is provided that will supply 52 in. dia. coils cut to any width down to 1 in. in the thickness range 0·08 –0·005 in. Another unit will cut sheets to any length between 24 and 192 in. in thicknesses from 0·08 to 0·01 in., and operates at a maximum speed of 350 ft/min.

NEW PLANT AND EQUIPMENT

Preparation of pipe ends and flanges

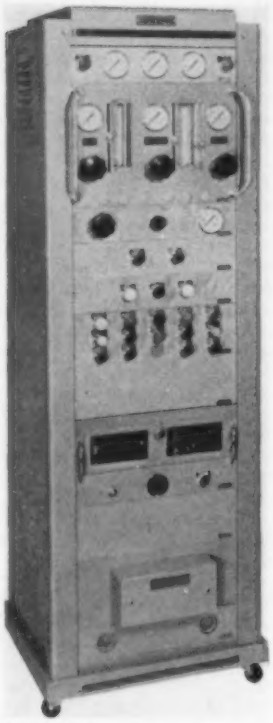
For the preparation of pipe ends and the facing and grooving of flanges *in situ*, David Reekie & Sons Ltd. have produced a series of portable 'Clydesdale' machines that are either electrically or pneumatically driven. The machines can

be operated in the vertical, horizontal, or inclined positions. Positive location is by means of clamping in the bore of the tube or, if the operation is required on irregularly shaped holes or on tubes larger than the specified capacity, by the use of internal locating jigs.

The four models now being produced can deal with facing and turning over a wide range of diameters, and one machine, which is clamped outside the tube, can bevel ends in tubes from $1\frac{3}{4}$ in. bore to $4\frac{1}{8}$ in. outside diameter.

Automatic control of metal spraying

Fully automatic electronic control can



METCO Type C control

be attained for heavy-duty and production metallizing by the use of the METCO Type C control system, introduced by Metallizing Equipment Co. Ltd.

The control unit is built on the 'module' unit system to provide flexibility and interchangeability, and will operate with both wire and powder metallizing techniques. The air, oxygen, and gas valves, connected to the main factory supplies, are electronically controlled to maintain pre-set values but there is automatic control to shut down the equipment should the air supply fall below the normal operating level, or should the flame fail. A remote control can be fitted so that several metallizing units can be operated from a master control panel.

With the wire technique the wire feed speed is again electronically controlled; for the idle condition the stopping of the feed also automatically reduces the gas and oxygen flow.

Welding meter

A meter for a.c. welding production, research, and development, designed to measure the electrical conditions in a welding arc, has been produced by the English Electric Co. Ltd.

The unit, measuring $16\frac{1}{2} \times 5\frac{3}{8} \times 6\frac{1}{2}$ in., comprises a watt-hour meter, ammeter, voltmeter, and protective relay. An additional item is a four-range current

English Electric welding meter

transformer for stepping down the supply current from 100, 300, 500 or 1000 amp to 5 amp.

STUB ENDS

▶Clyde Tube Forgings Ltd., manufacturers of welding pipe fittings, has been acquired from Shaw-Petrie Ltd. by the Chemetron Corporation of Chicago. The range of Clyde fittings will now be supplemented from the U.S.A. by Tube Turn fittings.

▶Three new ultra-high-strength steels for use at high-temperatures have been developed by Samuel Fox and Co. Ltd. The first is a commercial alloy already in production, HST 100 (previously known as Fox 769). The other two steels HST 120 and HST 140, with tensile strengths of 120 and 140 tons/sq.in. respectively, have been obtained by small compositional changes in the HST 100 analysis without an increase in carbon content.

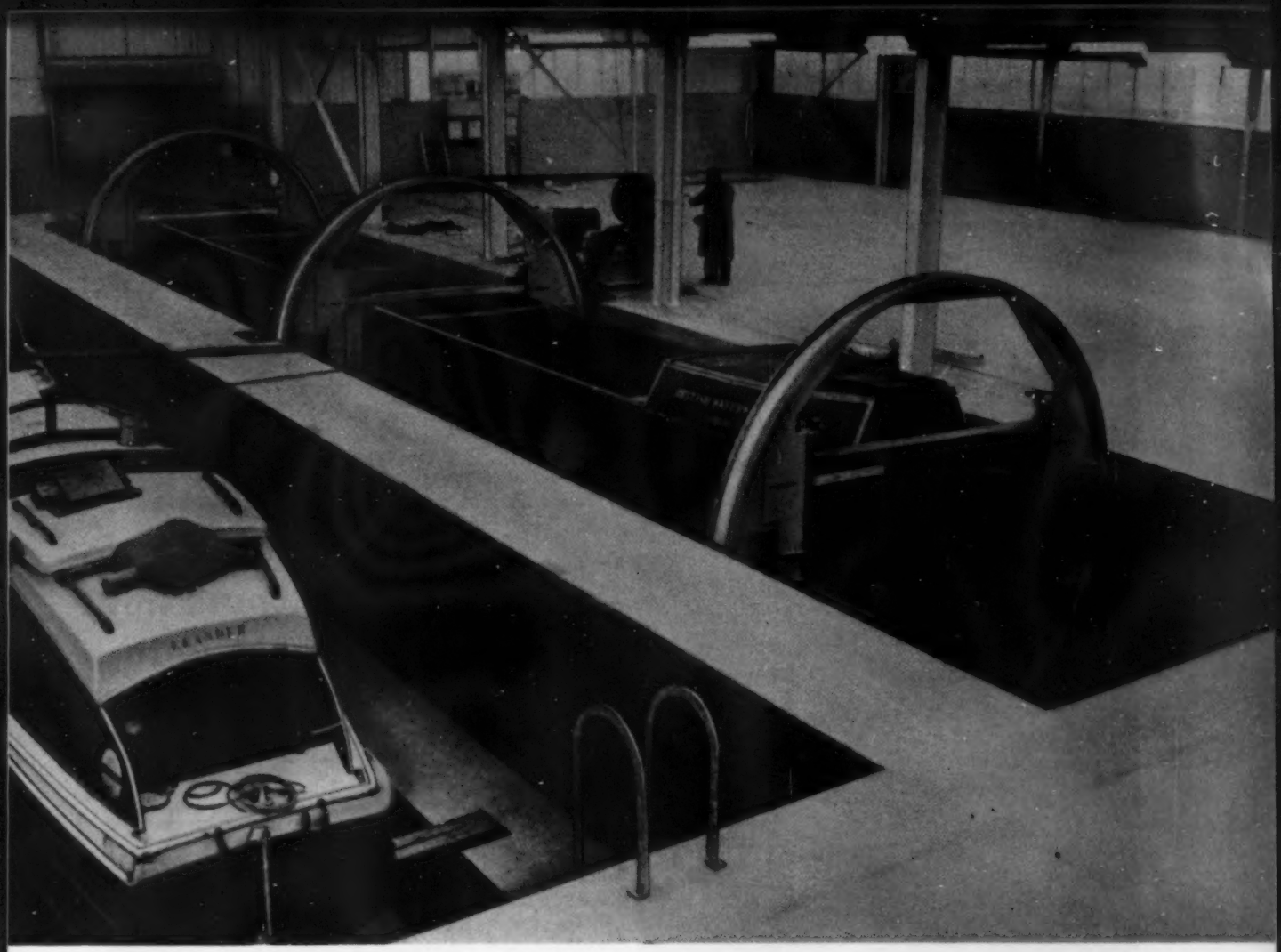
▶The third section of the American Welding Society *Welding Handbook* has now been published. It deals with some of the newer welding processes, allied processes, and oxygen and arc cutting.

▶Studies by the American Chain and Cable Co., presented in a paper by V. H. Godfrey to the A.W.S. Annual Meeting in April show that flat instead of round welding wire as used in the inert-gas processes gives better electrical contact, greater penetration, and smoother feeding and guidance.

▶Mr. W. Brining, F.C.A., of the Almin Group of Companies, has been elected 1960/61 President of the Aluminium Development Association in succession to Mr. R. Hahn.

▶Mr. W. F. Cartwright, Assistant Managing Director of the Steel Company of Wales Ltd., has been elected President of the Iron and Steel Institute for 1960/61.

▶ A colour film "Pipeline Construction" has recently been produced by Wm. Press & Son Ltd. It illustrates the civil engineering problems of a large pipeline undertaking, and describes the process of welding by the 'stove-pipe' method, and techniques of inspection and testing of the completed pipeline.



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Rotating barges up to 70 ft. in length and weighing 9 tons is a simple matter in the Ross manipulating equipment recently installed in the workshops of British Waterways at Bilston. This equipment was specially designed to rotate barges into any position for inspection and maintenance purposes in a new dry dock. The installation has many advantages. It simplifies maintenance work such as flame cleaning and repairs by welding; it reduces labour costs, provides safer working conditions and speeds up turnround time. The design of special holding and positioning equipment is a feature of the service offered by Donald Ross & Partners Ltd., to industry. Your enquiries will be welcomed.

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650 FEET OF WELD

The fuel tank, designed to be slung under the British Railways "Bo-Bo" locomotive is of an extremely complex construction and is made of aluminium to save weight on an already heavy locomotive. 650 feet of weld were involved—two thirds of which were inside the tank. Here the light weight of the Rowen-Gun made it a lot easier for the operators to get at the job and this accessibility considerably cuts down the time taken on each tank.

Another important point that came out was that the Rowen-Guns used comparatively little argon which resulted in big savings in cost on each tank.

The finished welded tank

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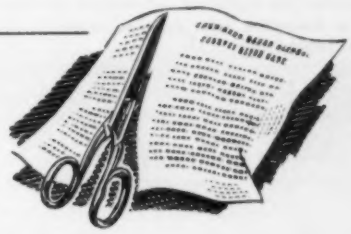

CONTENTS OF PERIODICALS RECEIVED

This section is intended to give a survey of the current welding literature received by the Institute of Welding Library. The contents lists are not exhaustive; only the main articles in welding journals are listed, and reprints from other journals and short notes are generally excluded. In addition, welding articles from other periodicals are listed. Abstracts of welding literature are given in the Bibliographical Bulletin of Welding and Allied Processes, *published by the International Institute of Welding, and details of this may be obtained from the Secretary of the Institute of Welding.*

Welding Journals

Australian Welding Journal, 1960, vol. 3, January

Methods of testing weldability, M. K. Shorshorov (9–11)

Welding as a career, F. Koenigsberger (12–14)

Journal of the Japan Welding Society, 1960, vol. 29, No. 2

Observations on the studies on weldabilities of structural quenched and tempered steels, Part 2, T. Yoshida and others (2–8)

Tungsten inert-gas arc-welding of mild steels, I. Sakakibara and others (9–15)

Directionality in hot rolled steel plates, Report 1, A. Kambayashi (16–19)

Effects of alloying elements on notch toughness of basic weld metals, Report 2, H. Sakaki (20–23)

The shapes and compositions of non-metallic inclusions in mild steel weld metals, Report 3, K. Kato (24–28)

On the maximum arc length in the metallic arc welding, F. Oshiba and K. Shimizu (29–36)

Strength of the brazed joint, Report 3, T. Yoshida and N. Nomura (37–39)

Study on soft soldering, Report 1, T. Kawasaki (40–45)

Some basic experiments of acetylene purifier, Report 1, I. Ueda and H. Shinotani (46–50)

Some investigations regarding oxygen cutting, Report 1, K. Suitsu and T. Yasuda (51–57)

Przegląd Spawalnictwa (Poland), 1960, vol. 12, May

Some research results in construction of pipe connections from 15HM steel, A. Tomaszewski

AS-9 automatic machine for vertical electro-slag welding, R. Kiecon

EPa-250 welding rectifier, J. Ozaist

Schweissen und Schneiden (Germany), 1960, vol. 12, April

Chemical-metallurgical investigations of welds, K. Born (139–146)

Comparative investigations into oxy-acetylene and oxy-arc gouging, H. von Hofe and St. Piwowar (146–153)

Schweisstechnik (Berlin), 1960, vol. 10, March

Welding equipment and welding sets in the Soviet Union, W. E. Paton (83–88)

Welding in the manufacture of diesel engines, O. Fratzscher (89–95)

On the possibility of investigating arc-phenomena during CO_2 welding by means of infra-red photography, Part 2, R. Probst and J. Wodara (95–100)

Current status and tendencies of development concerning compulsory fundamentals for instruction and examination of welders, H. Endter (100–103)

Attempts of alloy welding stock by admixture of a powder to the gas shielding in CO_2 welding, W. Gilde and E. Kretzschmar (104–105)

Schweisstechnik (Berlin), 1960, vol. 10, April

Carbon dioxide welding in the construction of machinery and equipment, H. Berger (113–117)

Automatic equipment and devices for three-phase arc-welding in heavy engineering, W. W. Stepanow (120–123)

Experiments for automatic testing of welds using ultrasonic inspection method, J. Angres (124–127); **Discussion**, F. Wulff (128–136)

Welding in nuclear engineering, E. Leinhos (128)

The welding of high alloy steels with special reference to corrosion, Part 2 and Conclusion, H. Jahre (137–141)

X-ray quality butt-joint assemblies, Part 2, K. G. Reinhardt and W. Knauer (142–148)

Aluminium welding guide for wrought alloys and casting alloys (156–157)

The Welder, 1959, vol. 28, October-December

Notes on the welding of steels having protective coatings, M. K. Williams (70–71)

Welding and Metal Fabrication, 1960, vol. 28, April

High speed car body production: automated assembly at the new pressed steel plant (130–139)

New plant for heavy fabrication (140–144)

Brazing nickel-containing alloys and stainless steels, J. Hinde and E. R. Perry (145–154)

Capacitor discharge welding (155–157)

Soldering stainless steels: the development of corrosion-resistant joints, D. C. Stock and W. J. Smellie (160–161)

Aluminium bronze welded fabrications, M. Birkhead and C. V. Wilson (162–168)

Welding Design and Fabrication (U.S.A.), 1960, vol. 33 March

The exotic metals: how to weld them, J. Huminik (29–30, 70)

Automation: the future for butt-welded stainless foil, (31, 61)

How to determine safe loads on eccentrically loaded weld groups (Tabular form) (32)

Techniques for crack-free surfacing of mill roll journals (34–35)

Welded aluminium trailers carry bigger payloads (36–37, 71)

How non-destructive testing aids in designing for welding (39–40)

Guide to non-destructive testing (41)

Four things to know about interpreting radiographic film (58–60)

Welding Design and Fabrication (U.S.A.), 1960, vol. 33, April

The impact of high-strength steels on the welding and fabricating industry (59–66)

Welded high-strength steels reduce weight of radar yoke by 25% (70–71, 73)

Techniques for ultrasonic testing of titanium pressure vessels, E. R. Foor (80–83)

New all-aluminium truss-type tower is all-welded (86–87)

Honeycomb production must increase 1,900 per cent by 1963 (88–90)

Welding Engineer (U.S.A.), 1960, vol. 45, April

How to weld T-1 steel (38–41)

New electrode developed by Navy for welding dynamically loaded T-1, J. S. Kobler (44–45)

Submerged-arc welded land clearing blade uses T-1 steel, R. Cunningham (46–47)

All welded coal hauler can carry five times its own weight (50)

Tests on T-1 steel include submerged-arc, CO_2-Mig welding (52)

Welding Journal (U.S.A.), 1960, vol. 39, March

Welded titanium case for space-probe rocket motor, A. J. Brothers and others (209–214)

Tungsten-arc cutting of stainless steel, G. A. Conner (215–221)

Enclosed welding of vertical grooves, J. A. N. Clevers and J. W. A. Stemerdink (223–228)

Analytical study of natural gas- oxygen cutting, theory and application, J. C. Worthington (229–235)

Spot welding of carbon steel, I. W. Johnson (89s–96s)

Spot and seam welding of Zircaloy 3, E. F. Nippes, W. F. Savage and K. C. Wu (97s–104s)

A study of cracking in low-alloy steel welded joints, J. T. Berry and R. C. Allan (105s–116s)

Exhaustion of ductility of E-steel in tension following compressive prestrain, D. C. Drucker, C. Mylonas and G. Lianis (117s–120s)

Dangers of arc strikes and a possible remedy, K. Winterton and J. M. Corbett (121s)

Development of oxidation- and liquid-sodium-resistant brazing alloys, D. Canonico and H. Schwartzbart (122s–128s)

Zeitschrift fur Schweisstechnik (Switzerland), 1960, vol. 50, January

The Tivoli to Coire bridge, J. Beusch (7–13)

The elevated cable railway (G 59) over the Zurichsee, C. G. Keel (2–6)

Zeitschrift fur Schweisstechnik (Switzerland), 1960, vol. 50, February

Examples of practical application of metal spraying using a gun, E. Blatti (30–36)

16,000°C with a plasma torch, F. Schad (36–39)

Zeitschrift für Schweisstechnik (Switzerland), 1960, vol. 50, March,

The use of devices aiding welding in the construction of penstocks, Part I, J. D. Schmid (77–79)

Code of symbolisation of filler metals used in gas surfacing, IIW Commission I (80–81)

Practical welding: repair of a crankshaft, F. Schott (90–91)

Other Journals

The new welding processes, J. C. Merriman (*Materials in Design Engineering* (U.S.A.), vol. 51, January, pp. 105–122)

How electroslag welding is used in Russia, A. B. Tesmen (*Metal Progress* (U.S.A.), 1960, vol. 77, February, pp. 118–122)

Approach to electroslag welding in the United States (*Metal Progress* (U.S.A.), 1960, vol. 77, February, pp. 123–125)

Producing aluminium alloy tubes by high-frequency resistance welding (*Pipes and Pipelines*, 1960, vol. 5, January, pp. vii–viii)

High temperature brazing experiments, R. R. Ruppender (*Metal Progress* (U.S.A.), 1960, vol. 77, February, pp. 95–97)

Which soft solder for nuclear service? A. B. Kaufman (*Materials in Design Engineering* (U.S.A.), 1960, vol. 51, February, pp. 87–90)

Which copper-base alloy for a brazed part? E. Belkin (*Materials in Design Engineering* (U.S.A.), 1960, vol. 51, March, pp. 114–116)

Contract metal spraying, G. A. Curson (*Electroplating and Metal Finishing*, 1960, vol. 13, March, pp. 91–94)

Low cost coatings for metal products, R. J. Fabian (*Materials in Design Engineering* (U.S.A.) 1960, vol. 51, March, pp. 123–138)

The nondestructive testing engineer—today's career opportunity. The 1959 Lester honor lecture, C. E. Betz (*Nondestructive Testing* (U.S.A.), 1960, vol. 18, January–February, pp. 15–26)

A nondestructive method to detect pipes and cavities in hot steel blooms during the rolling-process by means of betatron, X-ray-image-intensifier and television-setup, W. Lueckerath and others (*Nondestructive Testing* (U.S.A.), 1960, vol. 18, January–February, pp. 27–34)

Nondestructive testing in tropical areas, C. F. Meynart (*Nondestructive Testing* (U.S.A.), 1960, vol. 18, January–February, pp. 39–40)

Welding properties of steels, J. Lomas (*Machinery Lloyd*, 1960, vol. 32, No. 5, February 27, pp. 51, 53–54)

Welding aluminium bronze (*Metal Industry*, 1960, vol. 96, No. 6, February 5, pp. 105–107)

Success in fabricating aluminium-bronze (*Engineering*, 1960, vol. 189, February 5, p. 182)

Recent advances in joining aluminium, G. W. Eldridge (*Metallurgia*, 1960, vol. 61, February, pp. 55–60)

A modified phase diagram for stainless steel weld metals, W. T. DeLong (*Metal Progress* (U.S.A.), 1960, vol. 77, February, pp. 98–100)

Welding a pressure vessel for a Canadian test reactor, A. M. Bain, A. H. Clark, and M. J. Lavigne (*Metal Progress* (U.S.A.), 1960, vol. 77, January, pp. 96–100)

Stress fields as a necessary basis for a design responding to the strength required in the construction of cranes, W. Kloth (*Stahl und Eisen* (Germany), 1960, vol. 80, February 4, pp. 159–164)

Arc torch prepares tank seams (*Iron Age* (U.S.A.), 1960, vol. 185, February 25, pp. 66–67)

Promising precoated strip is a teaser (*Engineering*, 1960, vol. 189, March 18, pp. 374–375)

Honeycomb; Part 1, How to design honeycomb sandwich. Materials for sandwich construction, P. J. B. Stevens and L. M. Polentz (*Materials in Design Engineering* (U.S.A.), 1960, vol. 51, March, pp. 117–122, 172)

Applications of plastic-coated steel sheet and strip, W. N. Jenkins (*Sheet Metal Industries*, 1960, vol. 37, February, pp. 89–96)

Sprayed ceramic coatings, J. A. Sheppard (*Engineering Materials and Design*, 1960, vol. 3, May, pp. 288–290)

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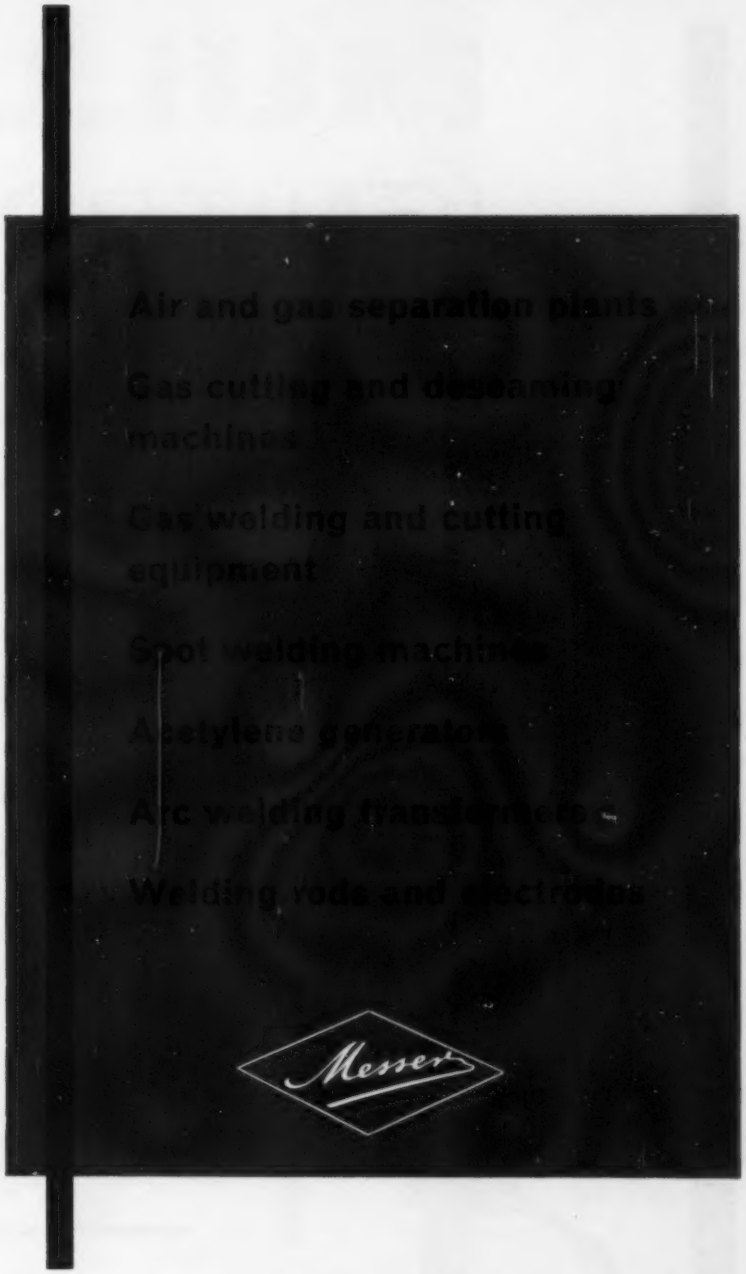

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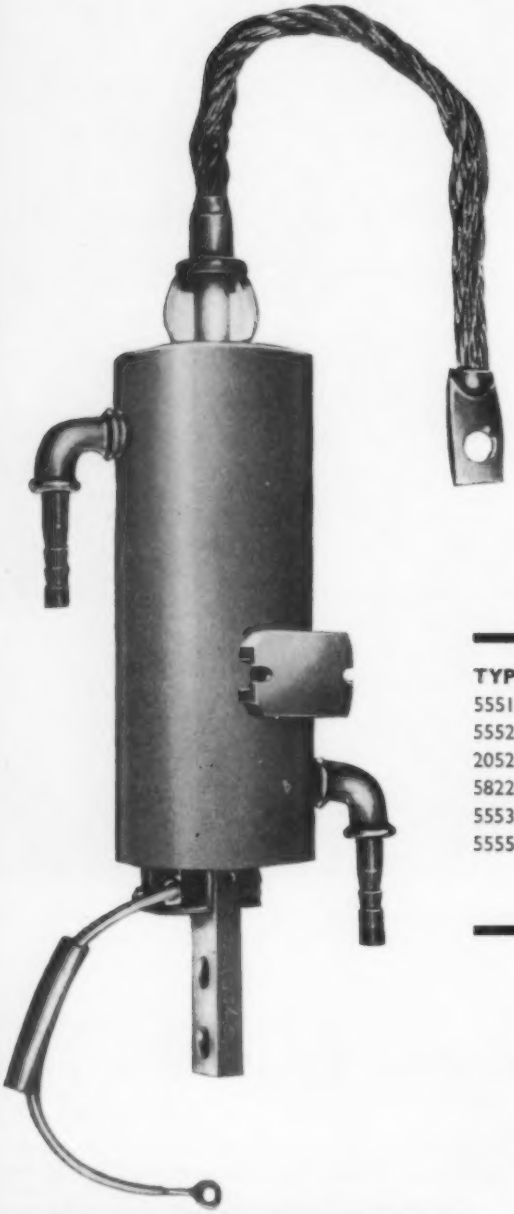

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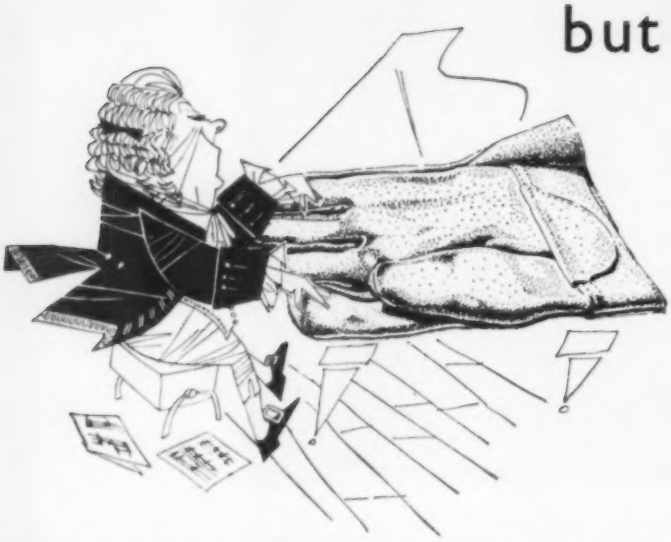

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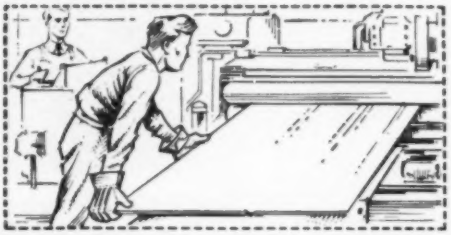

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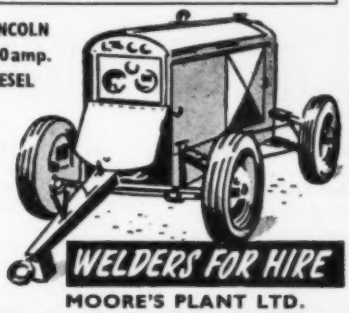

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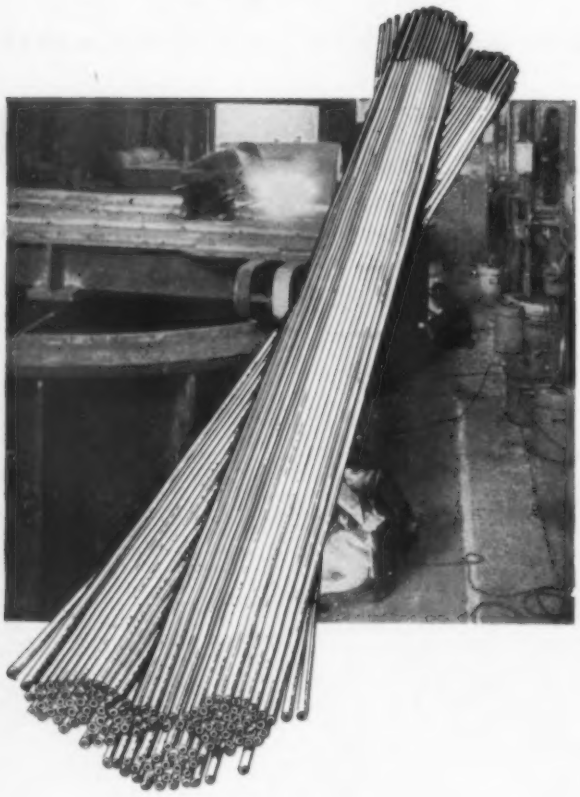

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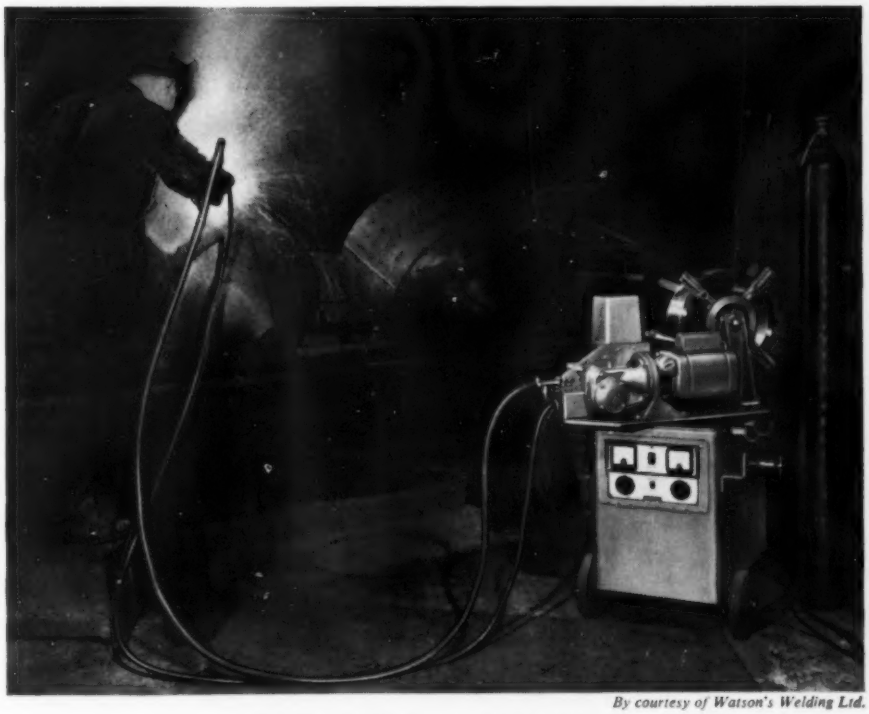

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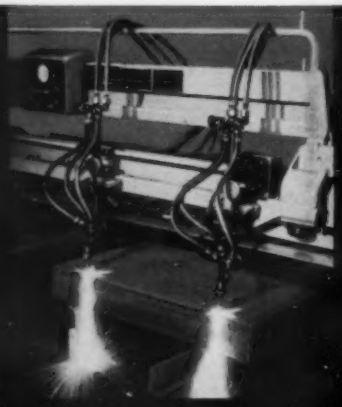

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